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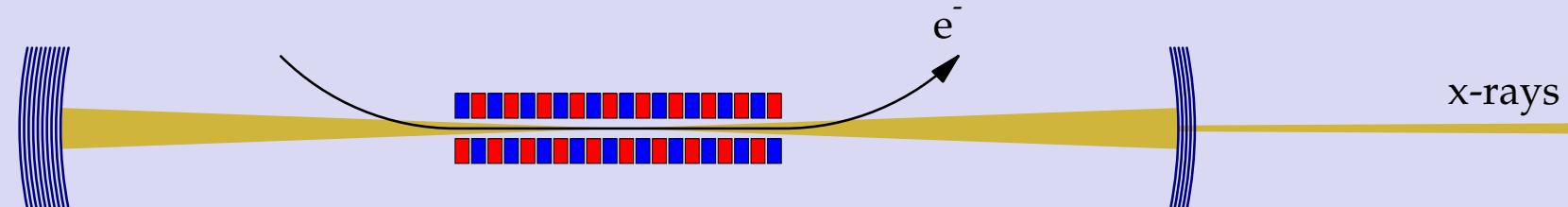


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X-Ray Free Electron Laser Oscillator With Crystal Cavity.

A Future Fully Coherent Hard X-ray Source

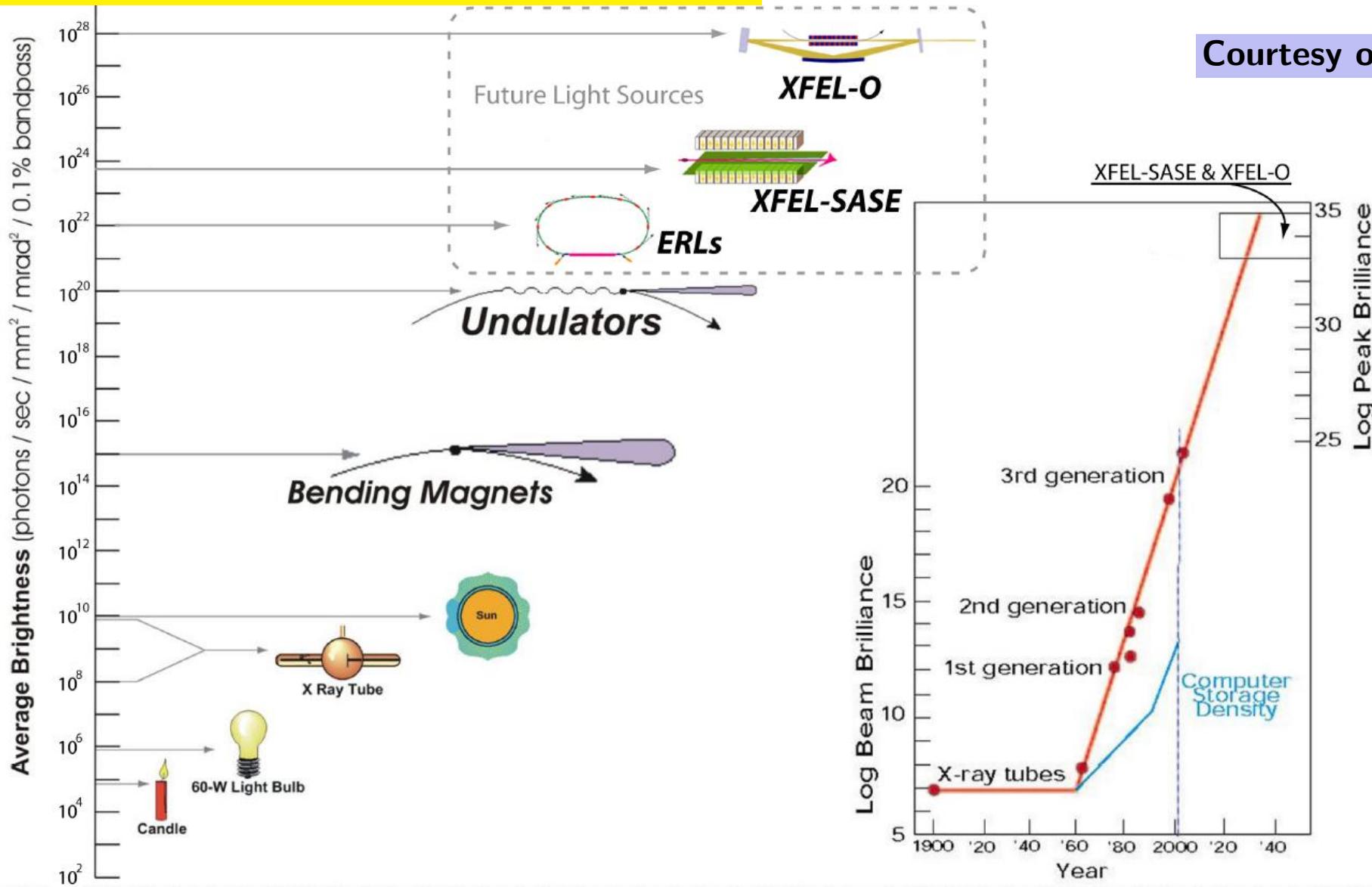
Yuri Shvyd'ko



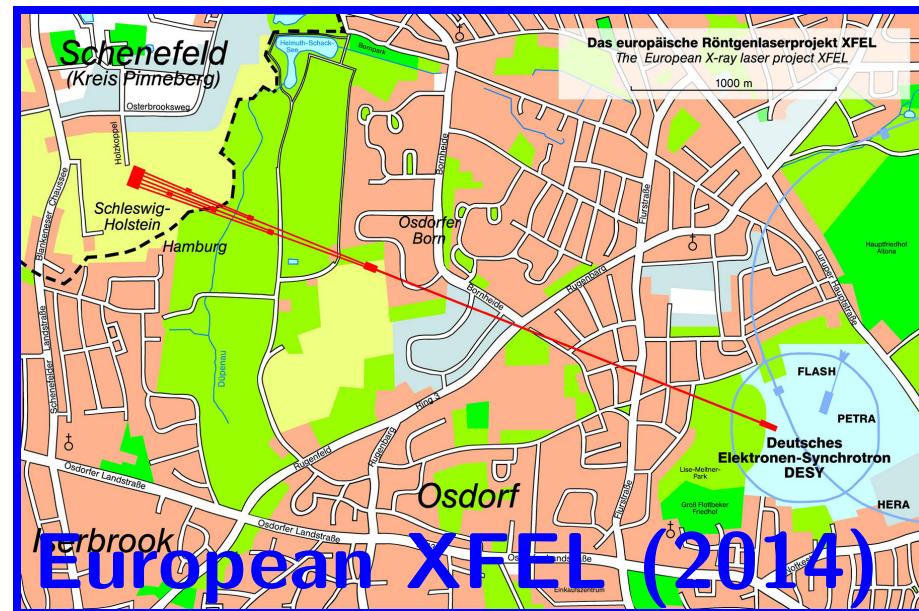
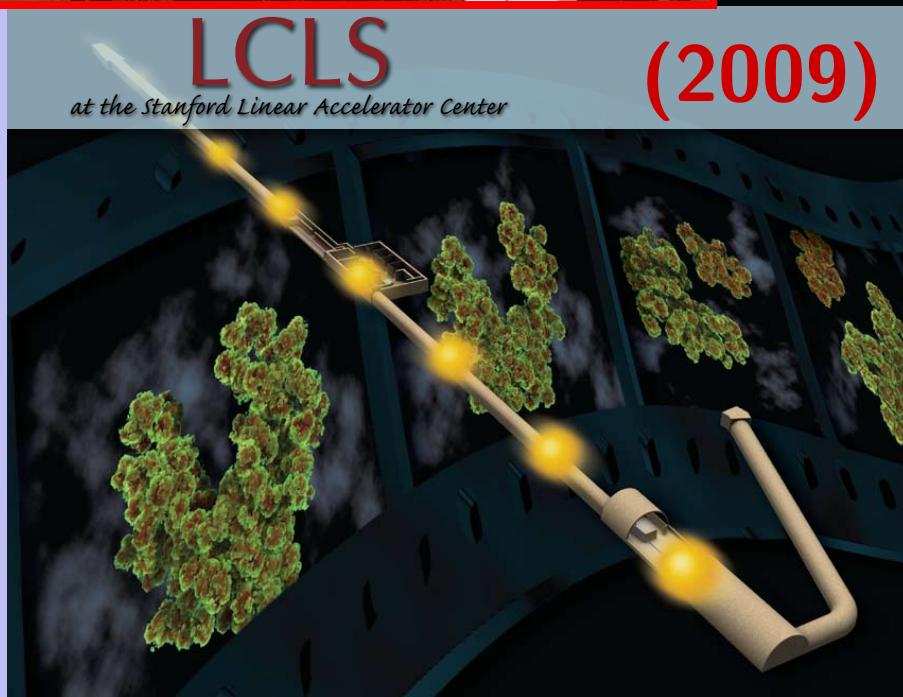
In collaboration with
K.-J. Kim, S. Reiche, R. Lindberg, S. Stoupin

Present and Future X-Ray Sources

Future: linac-based x-ray sources



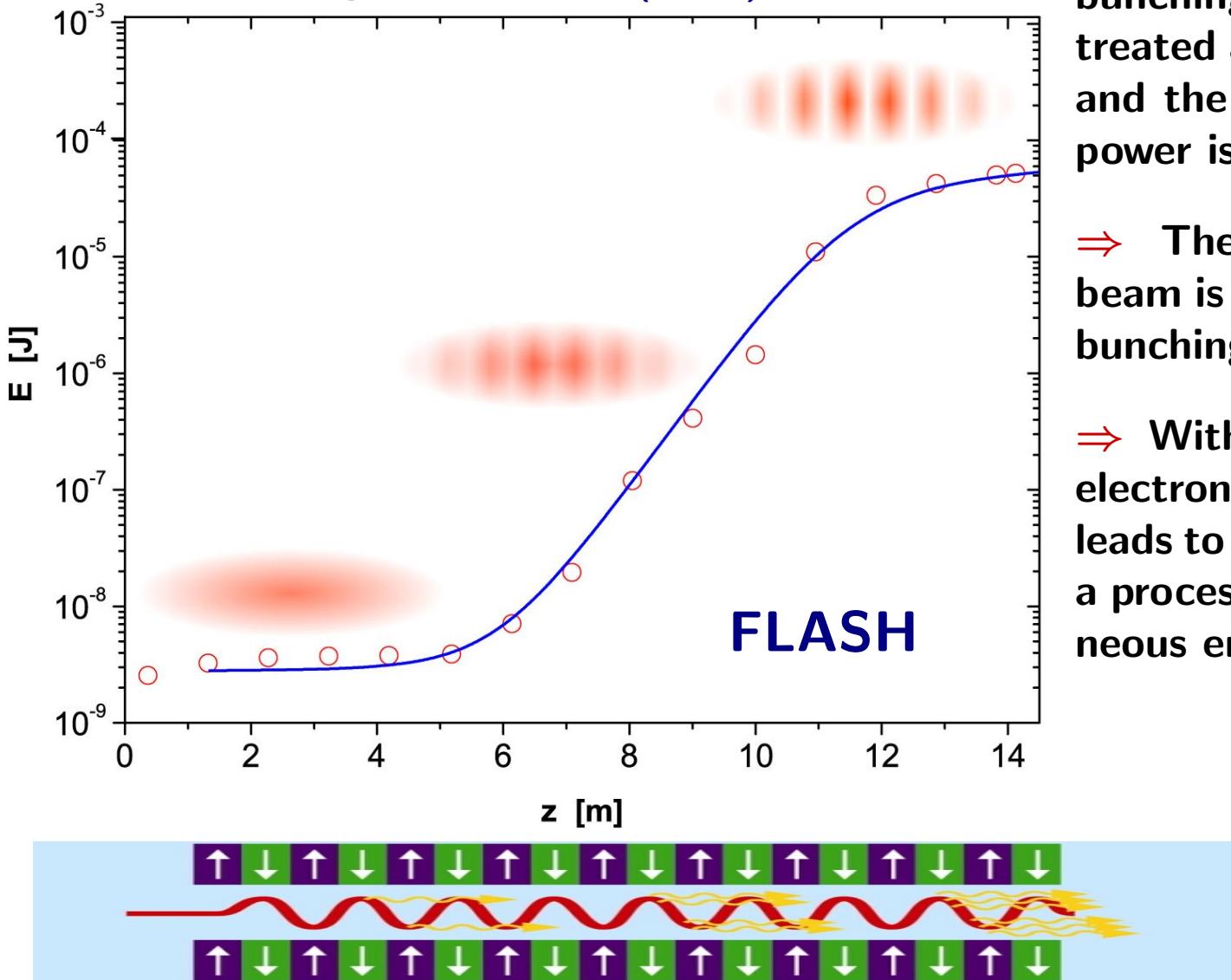
HG-XFEL Facilities



High-Gain SASE XFEL by Microbunching

Kondratenko, Saldin (1979)

Bonifacio, Pellegrini, Narducii (1984)



⇒ In the beginning without microbunching all the N electrons can be treated as individually radiating charges, and the resulting spontaneous emission power is proportional to N .

⇒ The shot noise of the electron beam is amplified up to complete microbunching.

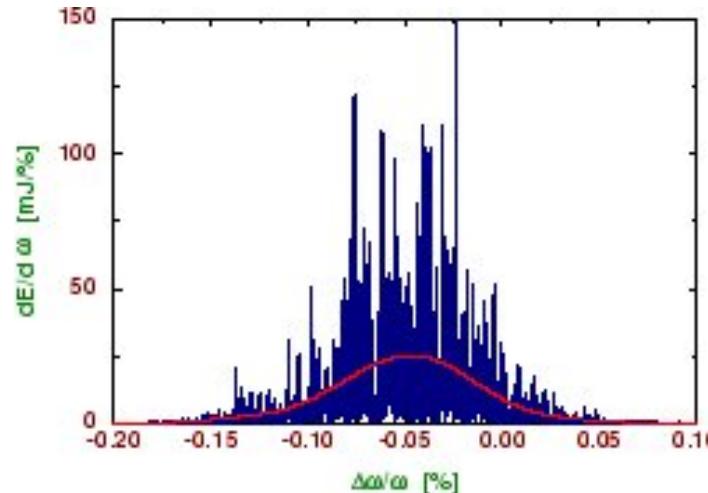
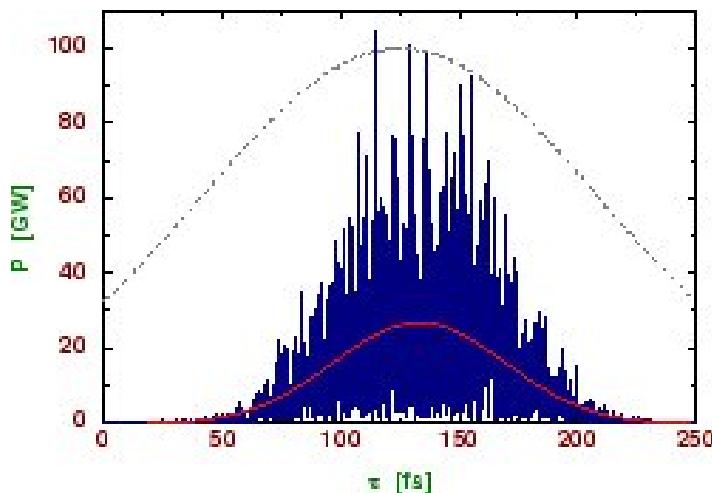
⇒ With complete micro-bunching, all electrons radiate almost in phase. This leads to a radiation power growth as N^2 , a process called self-amplified spontaneous emission (SASE)

Requires electron beams:

- emittance $\epsilon_n \lesssim 10^{-6} \text{ m rad}$
- energy $E_e \simeq 10 \text{ GeV}$
- energy spread $\frac{\sigma_E}{E_e} \lesssim 10^{-4}$
- peak current $\simeq 10^4 \text{ A}$
- pulse length $< 100 \text{ fs}$

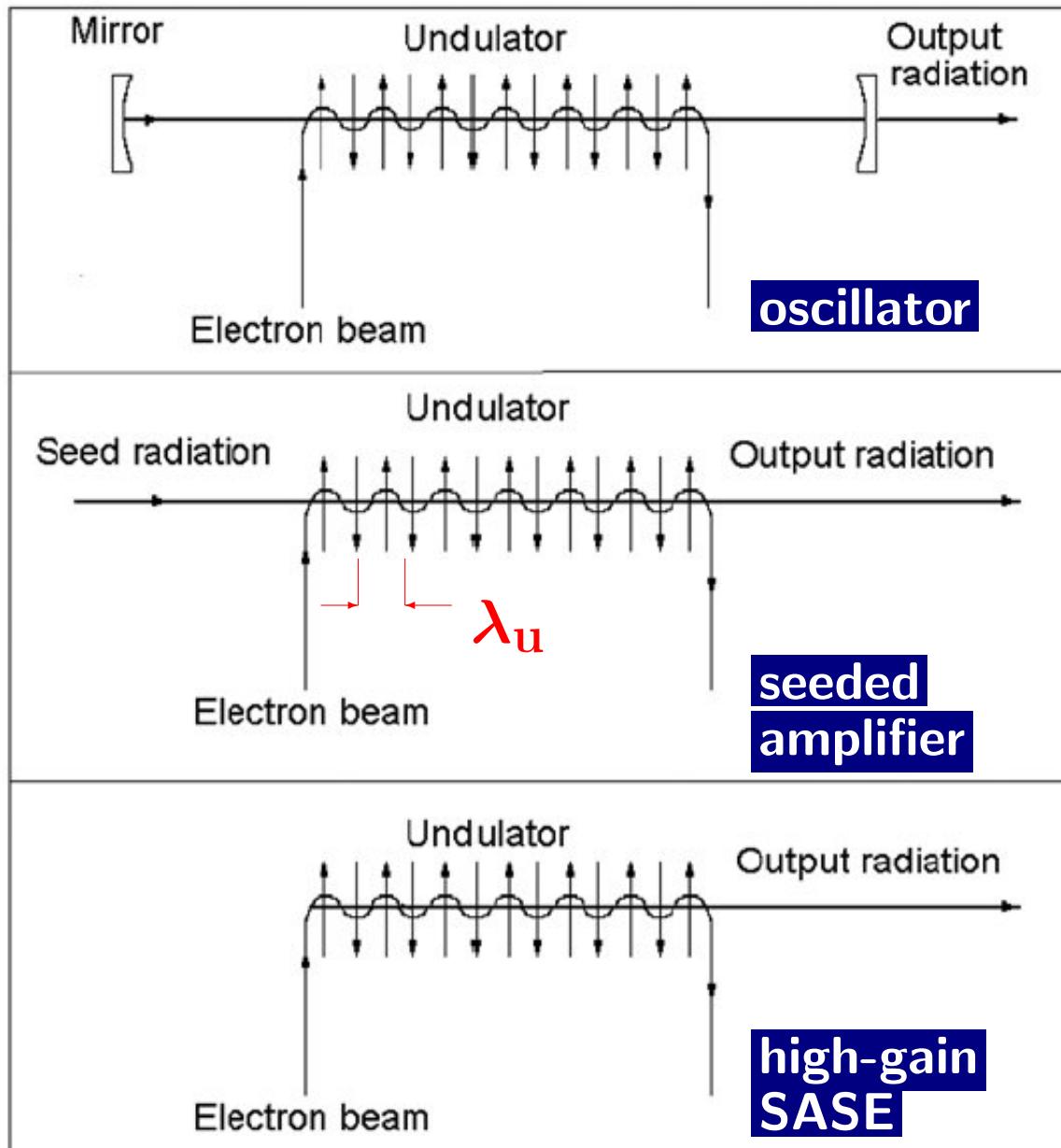
Coherent Properties of the HG-XFEL Radiation

- The radiation from a SASE XFEL is fully transversely coherent, nearly Fourier transform limited.
- Temporal coherence is low because of the start-up from noise.



- Seeded **FEL amplifier** or **FEL oscillator** would generate radiation with better coherent properties.

FEL configurations



The essential advantage of FEL radiation as compared to undulator radiation is its much higher intensity because a large number N of electrons radiate coherently: $\propto N^2$, producing a clean superradiant pulse.

Require electron beams:

emittance $\varepsilon_n \lesssim 10^{-6}$ m rad

energy $E_e \simeq 10$ GeV

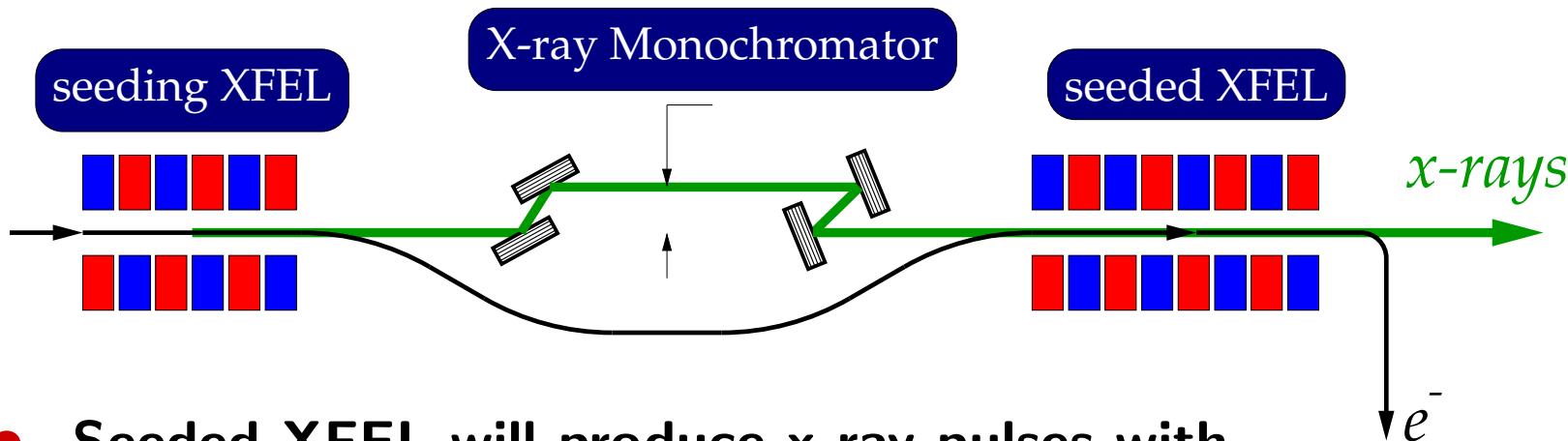
energy spread $\frac{\sigma_E}{E_e} \lesssim 10^{-4}$

peak current $10 - 10^4$ A

Resonance condition:

$$\lambda = \frac{\lambda_u}{2\gamma^2}(1 + K^2)$$

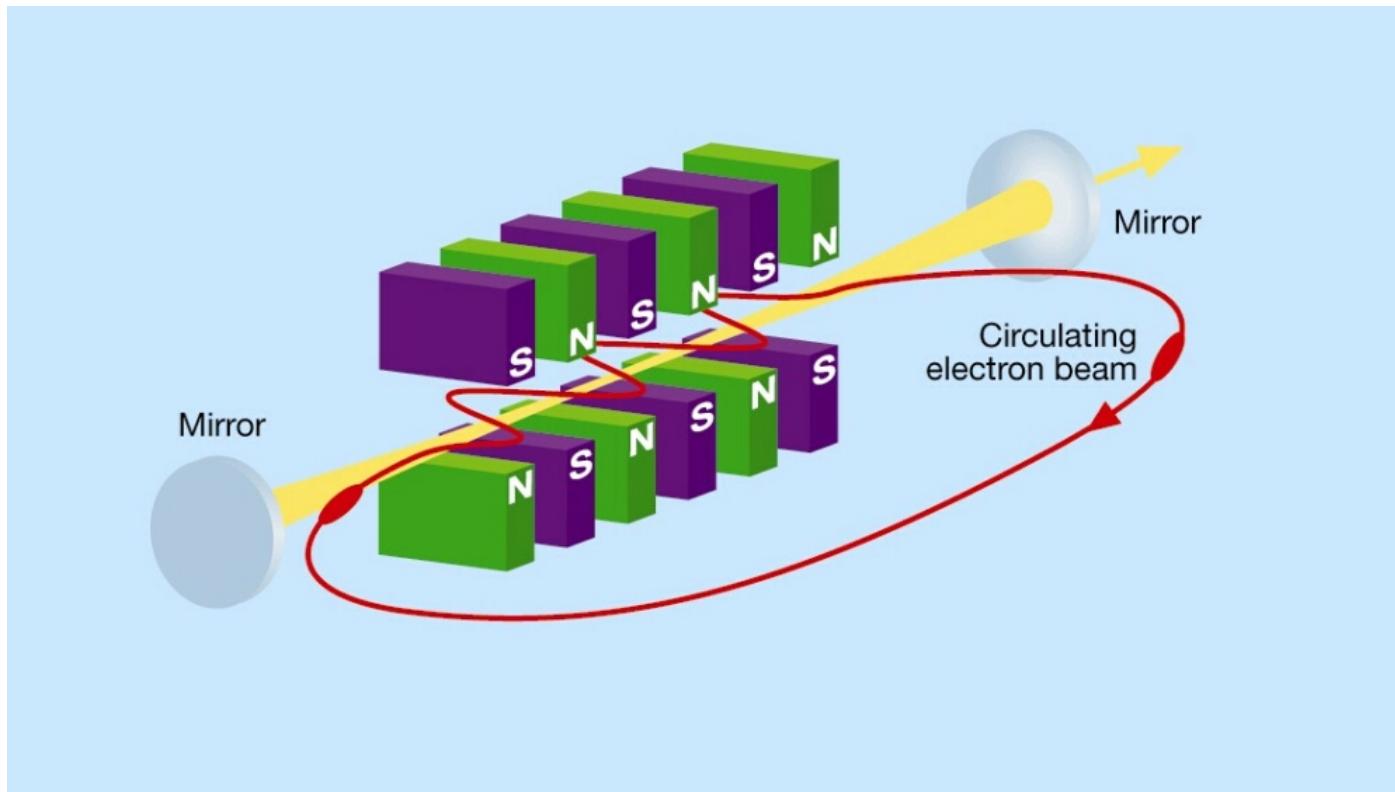
Seeded (Two-Stage) XFEL



- Seeded XFEL will produce x-ray pulses with
 - $\simeq 9 \times 10^{11}$ photons/pulse ($2 \text{ mJ/pulse} = 20 \text{ GW}$)
 - $\simeq 4 \times 10^{16}$ photons/s (100 W)
 - **transversely and temporarily coherent**
 - $\Delta E \approx 20 \text{ meV}$ (rms) close to the limit given by the pulse duration $\tau_e \approx 0.1 \text{ ps}$ (rms).
- Considered as upgrade of the European XFEL (>2014).
- E.L. Saldin, E.A. Schneidmiller, Yu.V. Shvyd'ko, and M.V. Yurkov, "X-ray FEL with a meV bandwidth", NIM, A475 (2001) 357-362.
- The Technical Design Report of the European XFEL, July 2007

Is an XFEL-Oscillator Feasible?

First proposal: Colella and Luccio (1984)



FELs based on the oscillator principle are limited, on the short-wavelength side, to ultraviolet wavelengths, primarily because of **mirror limitations**.

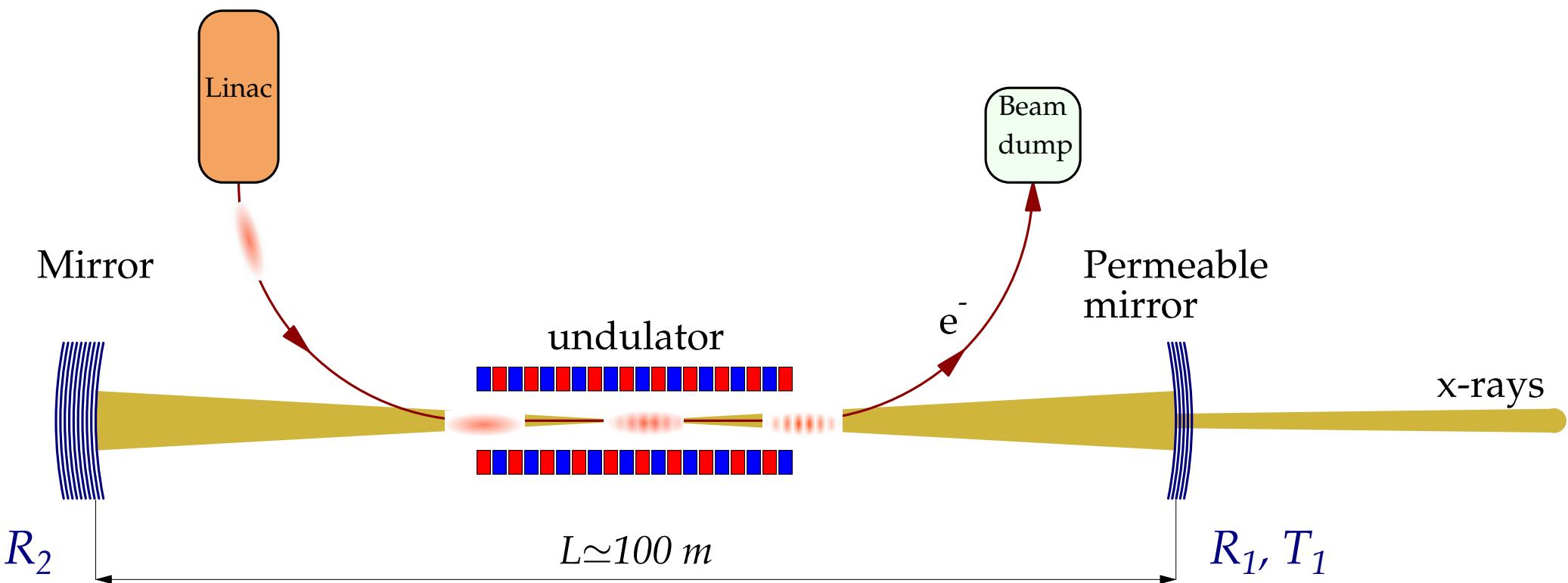
Free-electron lasing at wavelengths shorter than ultraviolet **can be achieved with a single-pass, high-gain FEL amplifier only**.

(The Technical Design Report of the European XFEL, July 2007)

XFEL-Oscillator Feasibility

- Low-gain XFELO is feasible based on:
 - low-loss x-ray crystal cavity (losses $\simeq 15\%$),
 - ultra-low-emittance ($\epsilon_n \lesssim 10^{-7}$ m rad) electron beams.
 - K.-J. Kim, Yu. Shvyd'ko, S. Reicher, PRL 100 (2008) 244802.
-

X-FEL Oscillator Principles

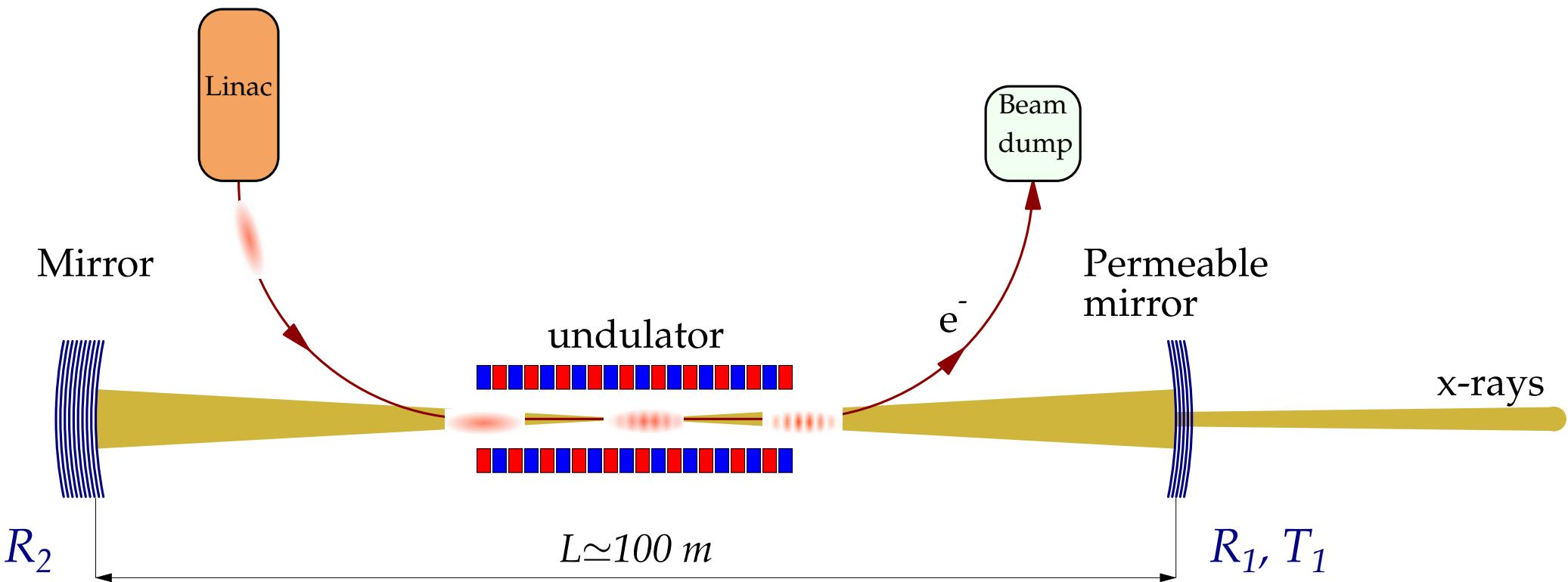


High repetition rate is required: $\nu = c/2L \simeq 1 \text{ MHz}$.

With $I_p \simeq 10 \text{ A}$, $\tau_p \simeq 1 \text{ ps}$, $\epsilon_n \simeq 10^{-7} \text{ m rad}$:

Gain $G = 10 - 20 \%$ is feasible

X-FEL Oscillator Principles



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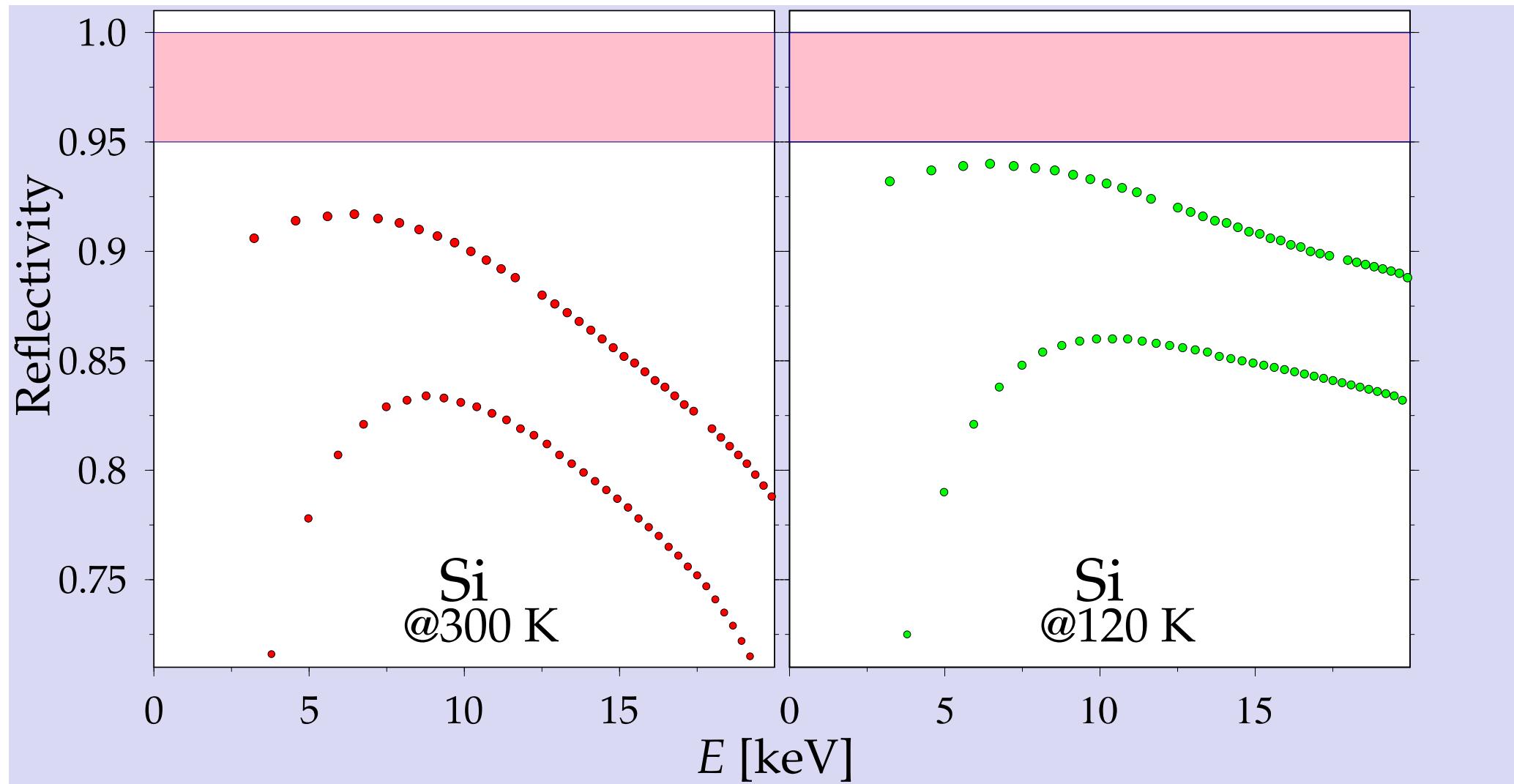
Small gain requires

low-loss optical cavity:

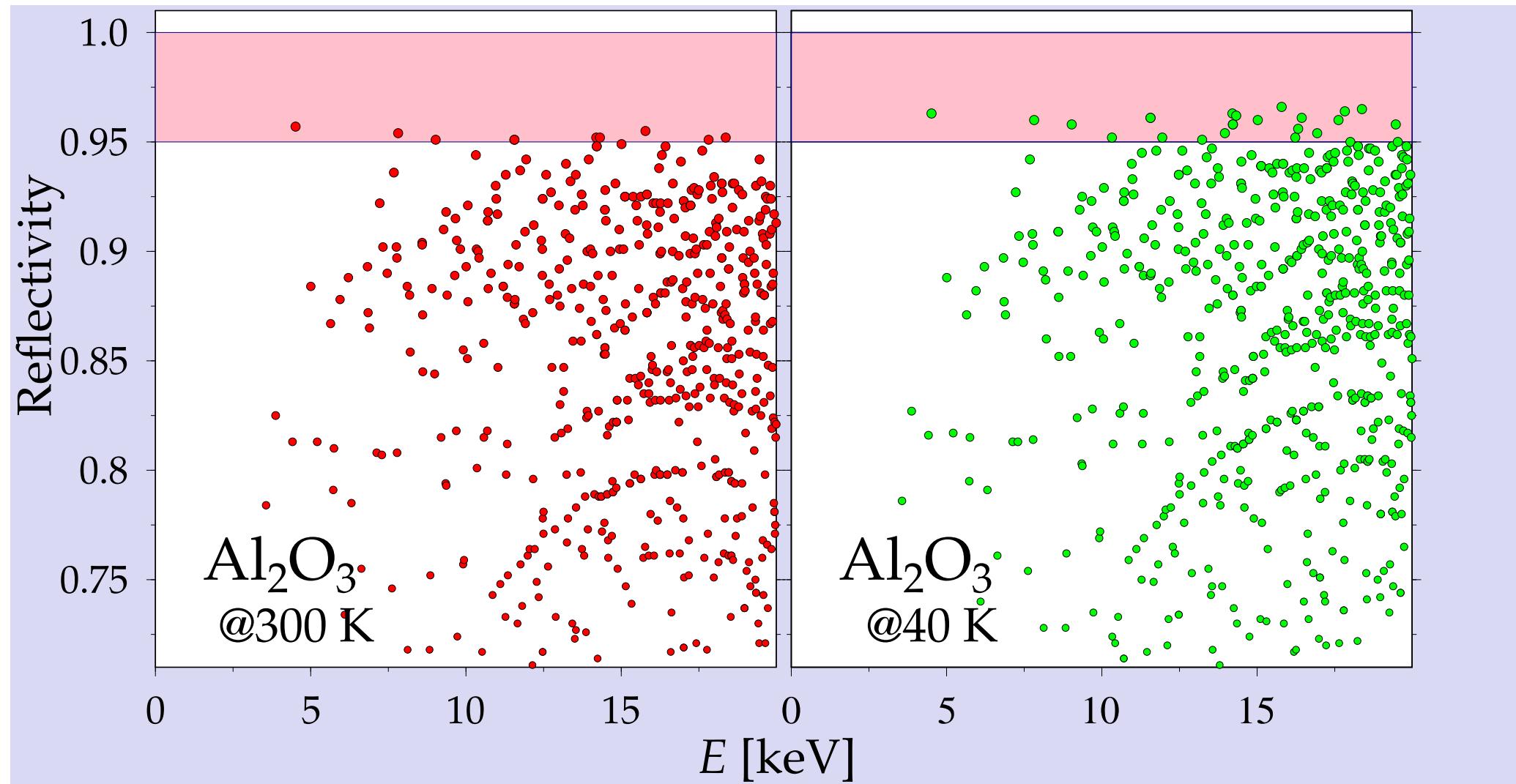
$$R_1 \times R_2 > 90\%$$

$$R_1, R_2 > 95\%$$

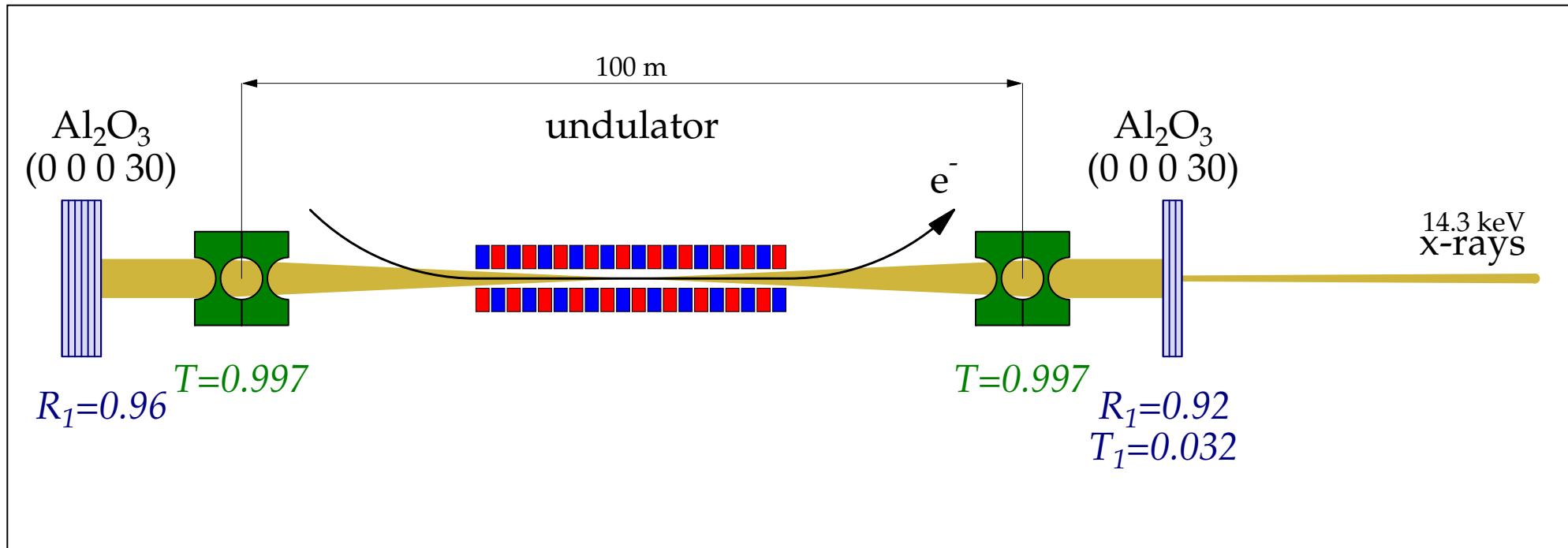
Reflectivity of Si in backscattering



Reflectivity of sapphire in backscattering



Sapphire cavity with CRL



$$R_1 \times R_2 \times T^4 = 0.87$$

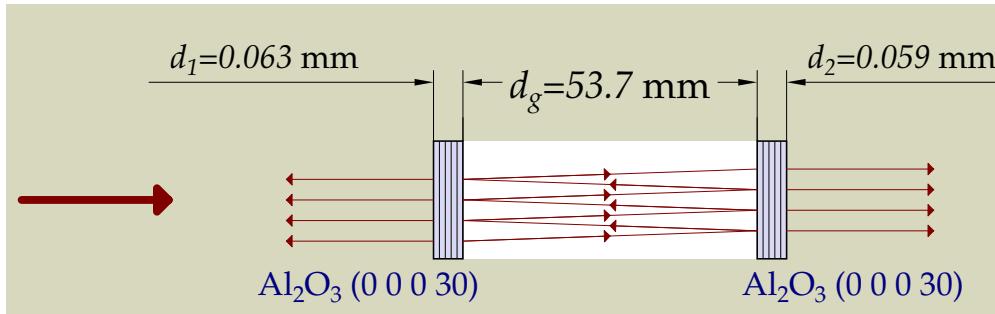
$$T_1 \simeq 0.032$$

CRL: $F = R/2N\delta = 50$ m

[$R = 0.333$ mm; $N = 2$; $\delta = 1.6 \times 10^{-6}$]

B. Lengeler, C. Schroer, et al, JSR 6 (1999) 1153

Sapphire X-ray resonator demonstrated

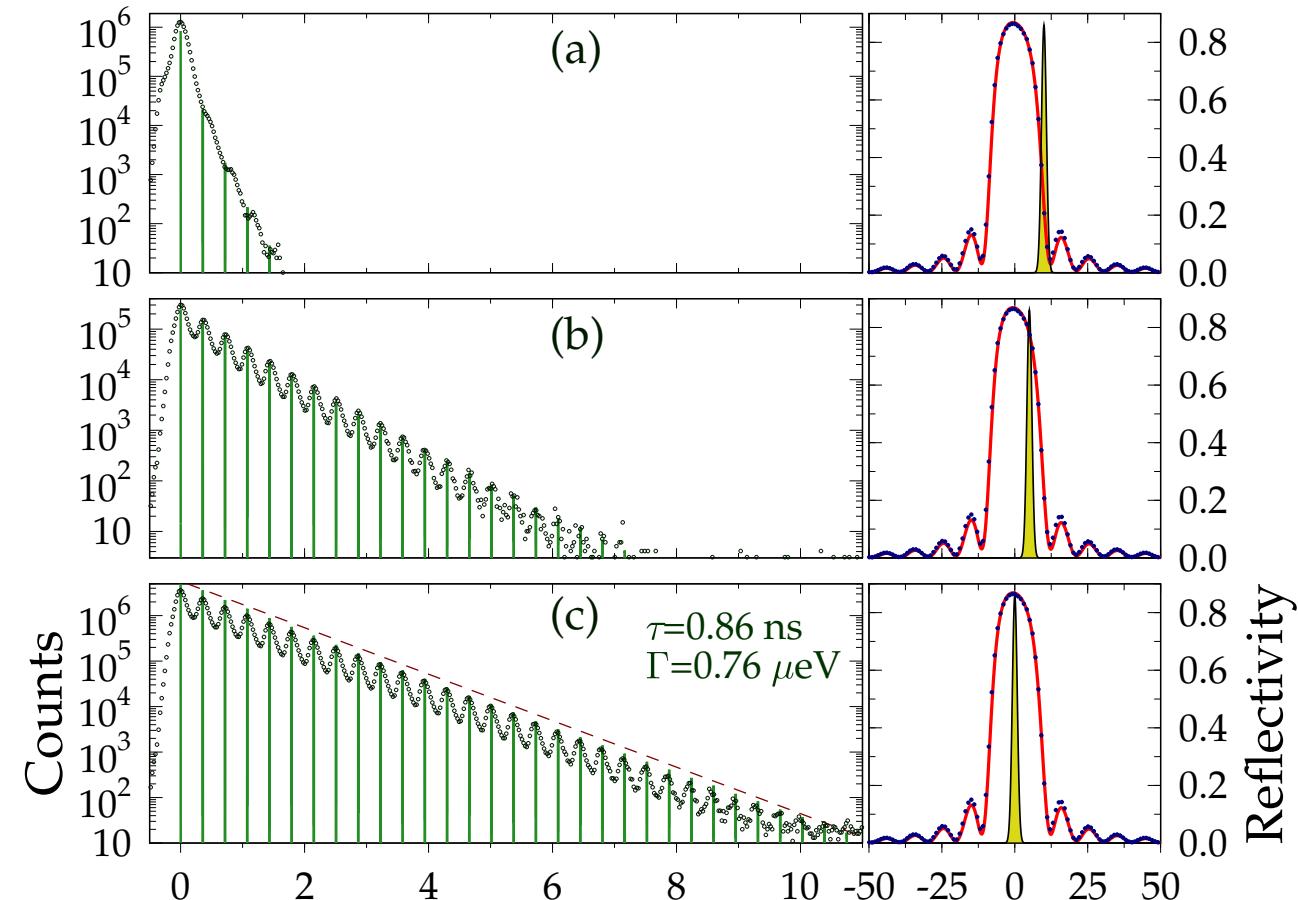


Shvyd'ko, Lerche, Wille et al, *PRL* 90 (2003) 013904

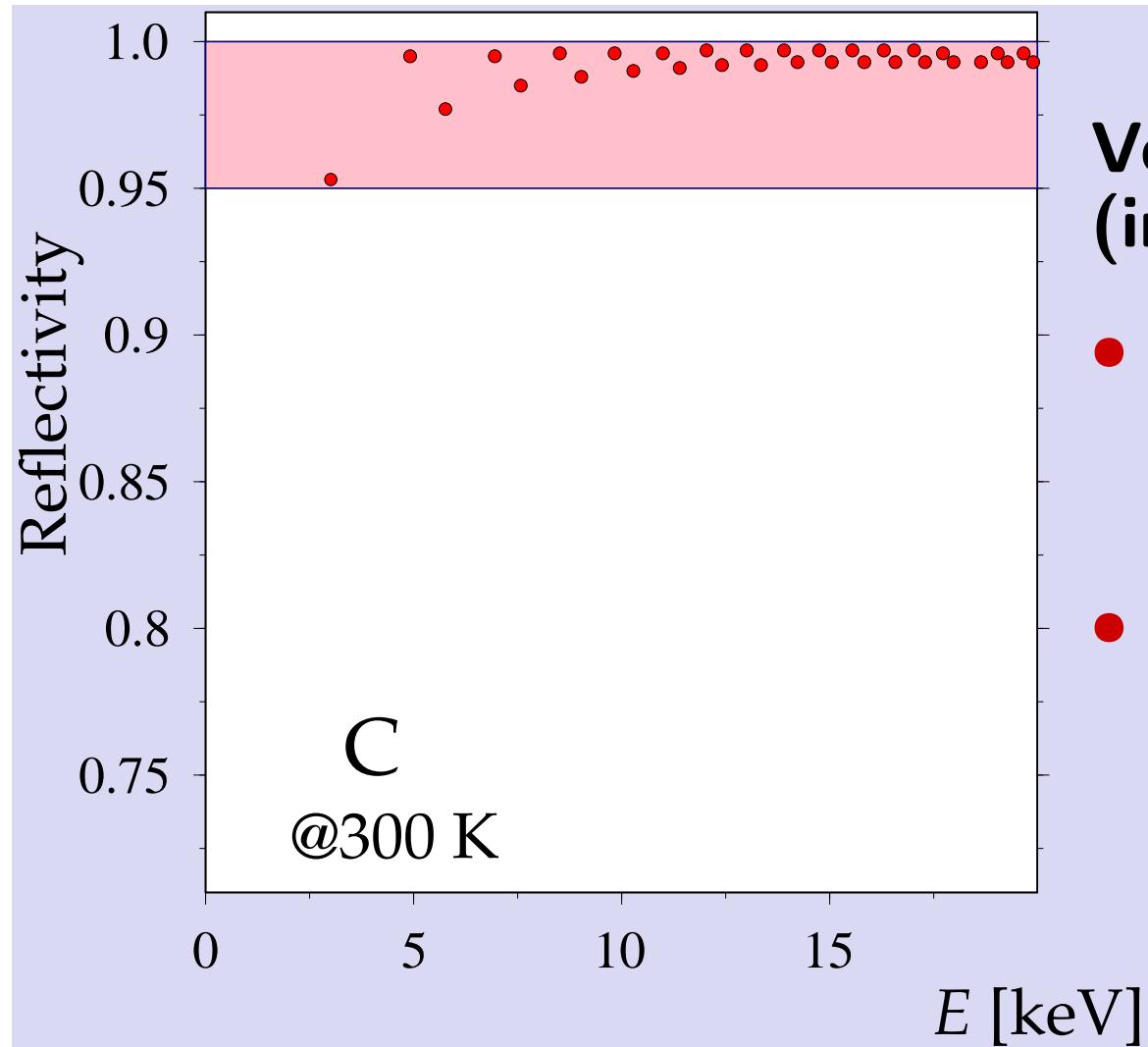
Measured finesse = 15

Measured reflectivity = 0.82

Expected reflectivity = 0.86



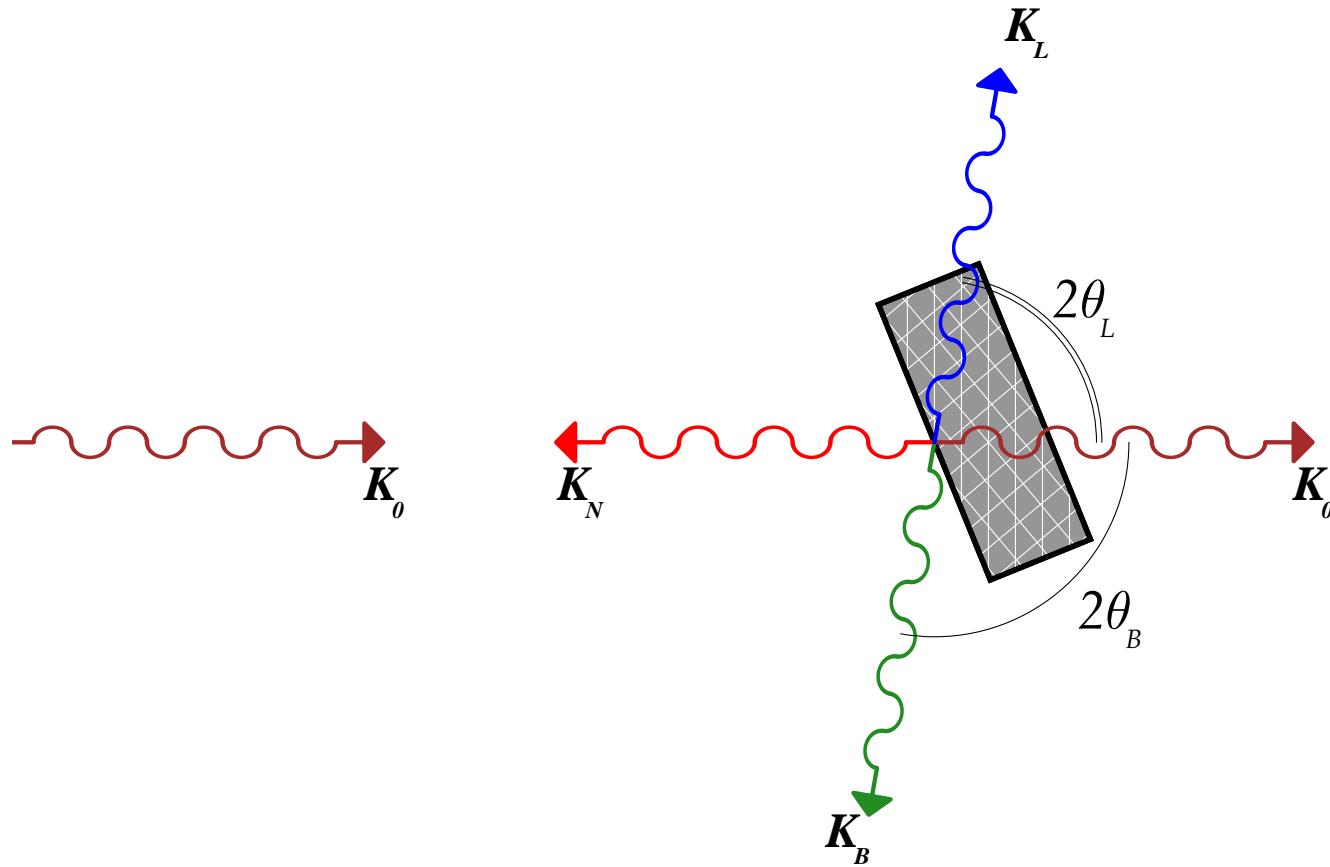
Reflectivity of diamond in backscattering



**Very high reflectivity
(in theory) due to:**

- High Debye Temperature, and thus high Debye-Waller factor
- Low Z , low photo absorption

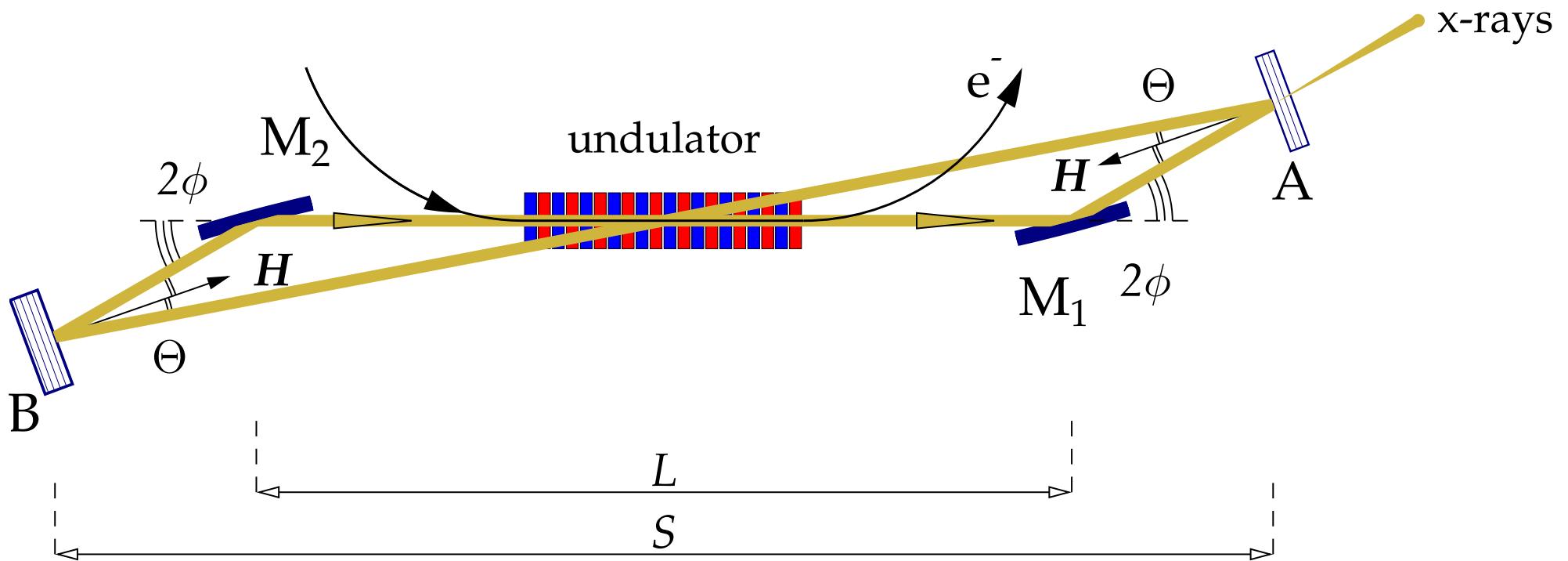
Multiple-beam Bragg Diffraction in Backscattering



Bragg-reflection condition can be fulfilled simultaneously for more than one reflecting atomic plane. In backscattering from Si, C, crystal this happens for all Bragg reflections except (111) and (220).

Si and C are not favorable as X-ray exact-backscattering mirrors

Diamond cavity for the X-FEL Oscillator

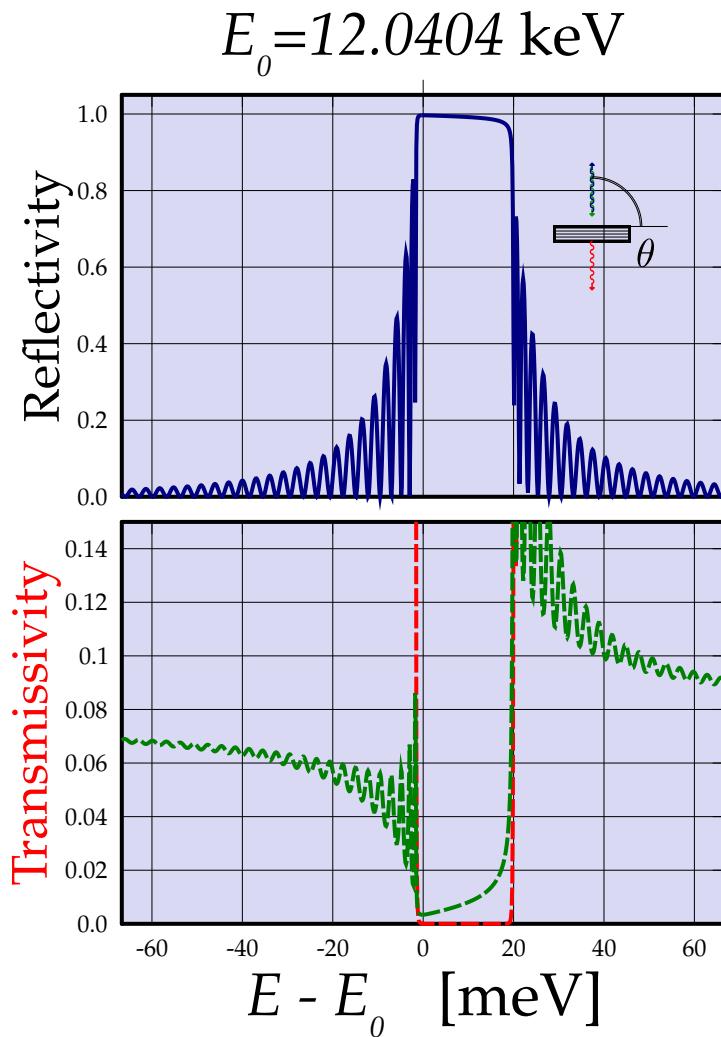


$$R_A \times R_B \times R_{M_1} \times R_{M_2} \simeq 0.9$$

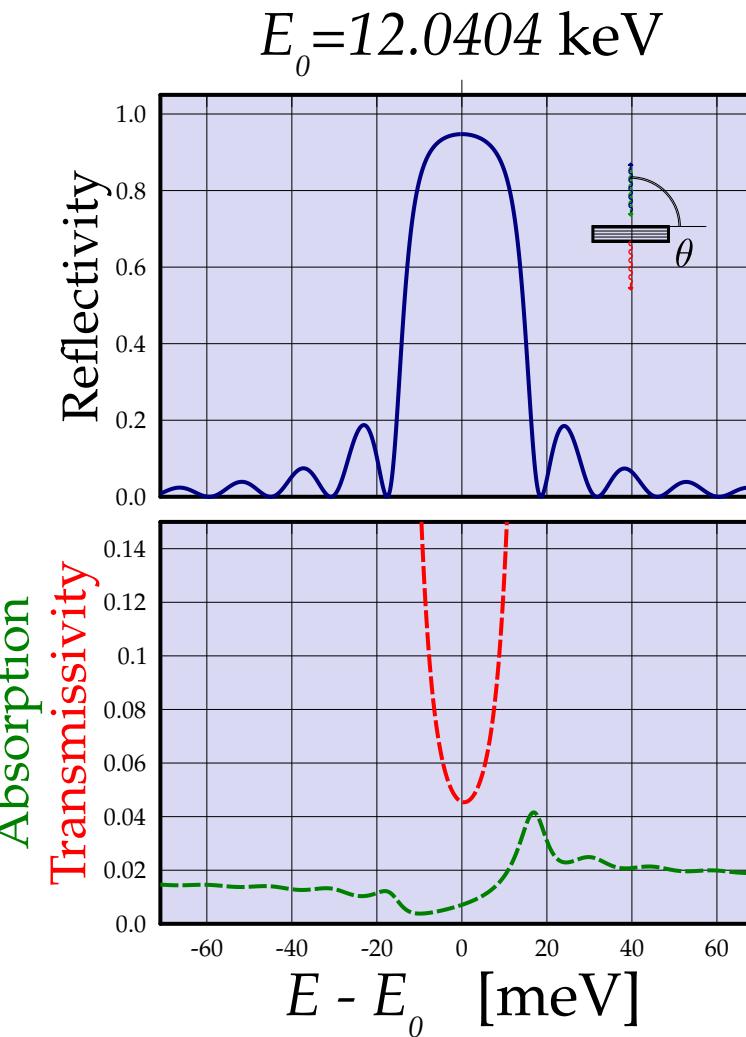
$$T_A \simeq 0.04$$

Diamond crystal and mirror reflectivity @ 12 keV

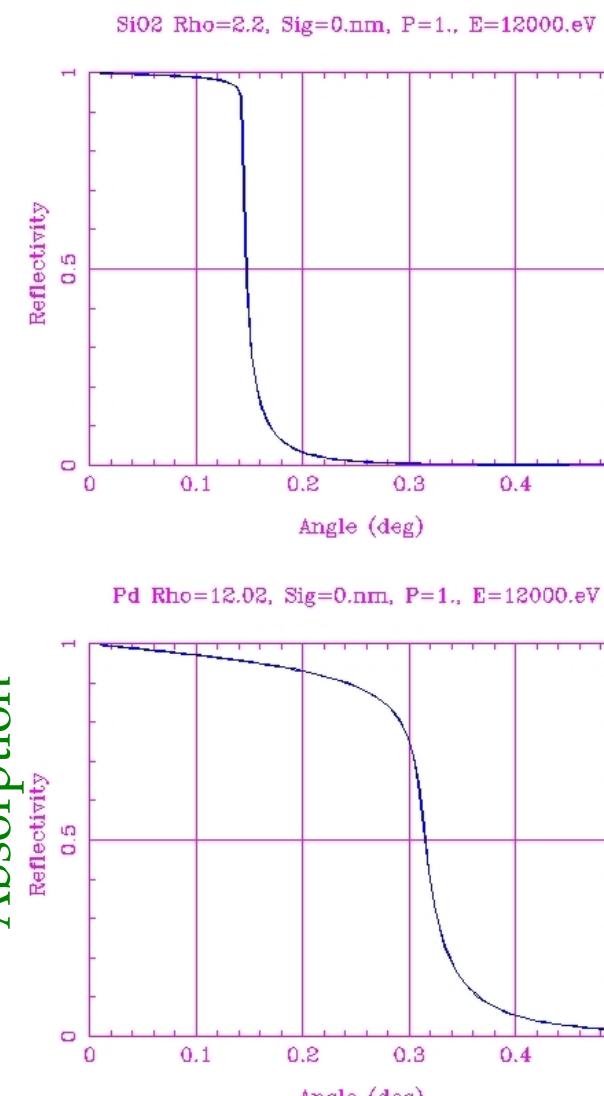
Narrow band mirrors: $\Delta E \approx 10 \text{ meV}$; $\Delta E \approx \hbar/\tau_p$



C(4 4 4); L = 0.2 mm; T = 300 K
bradix version: January, 2007

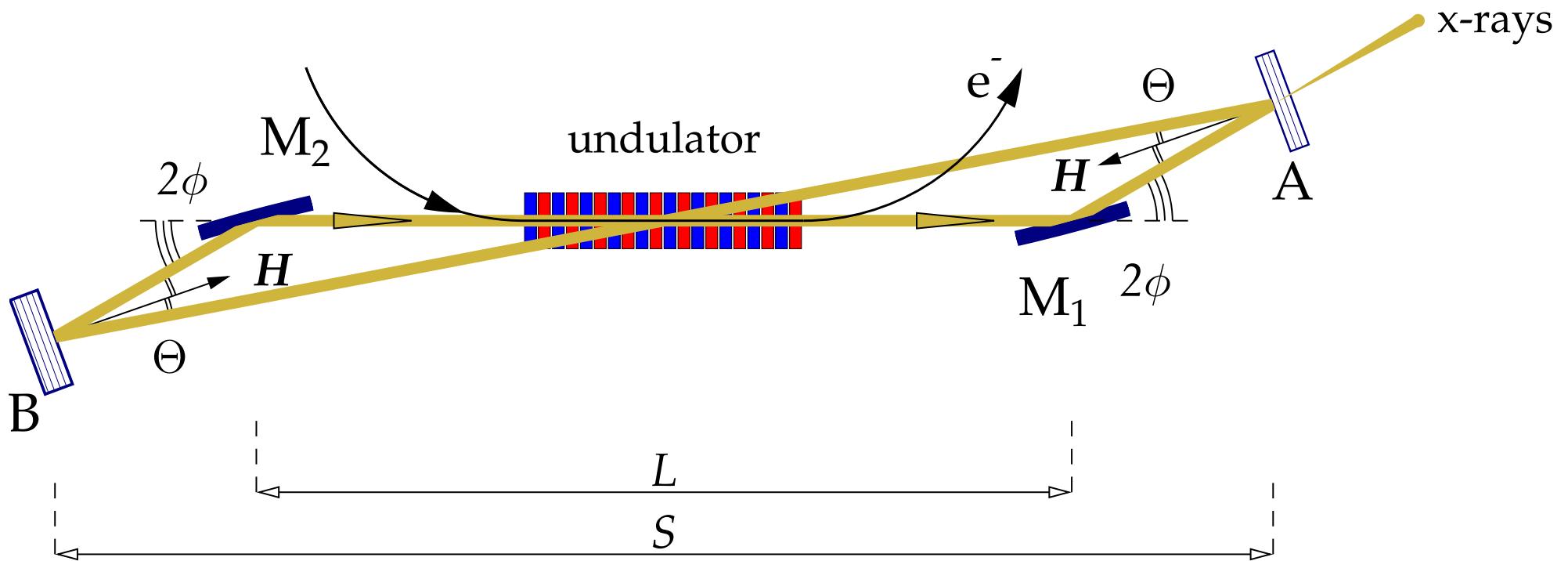


C(4 4 4); L = 0.042 mm; T = 300 K
bradix version: January, 2007



Mirror calculations:
www-cxro.lbl.gov

Two-Crystal Cavity is not Tunable

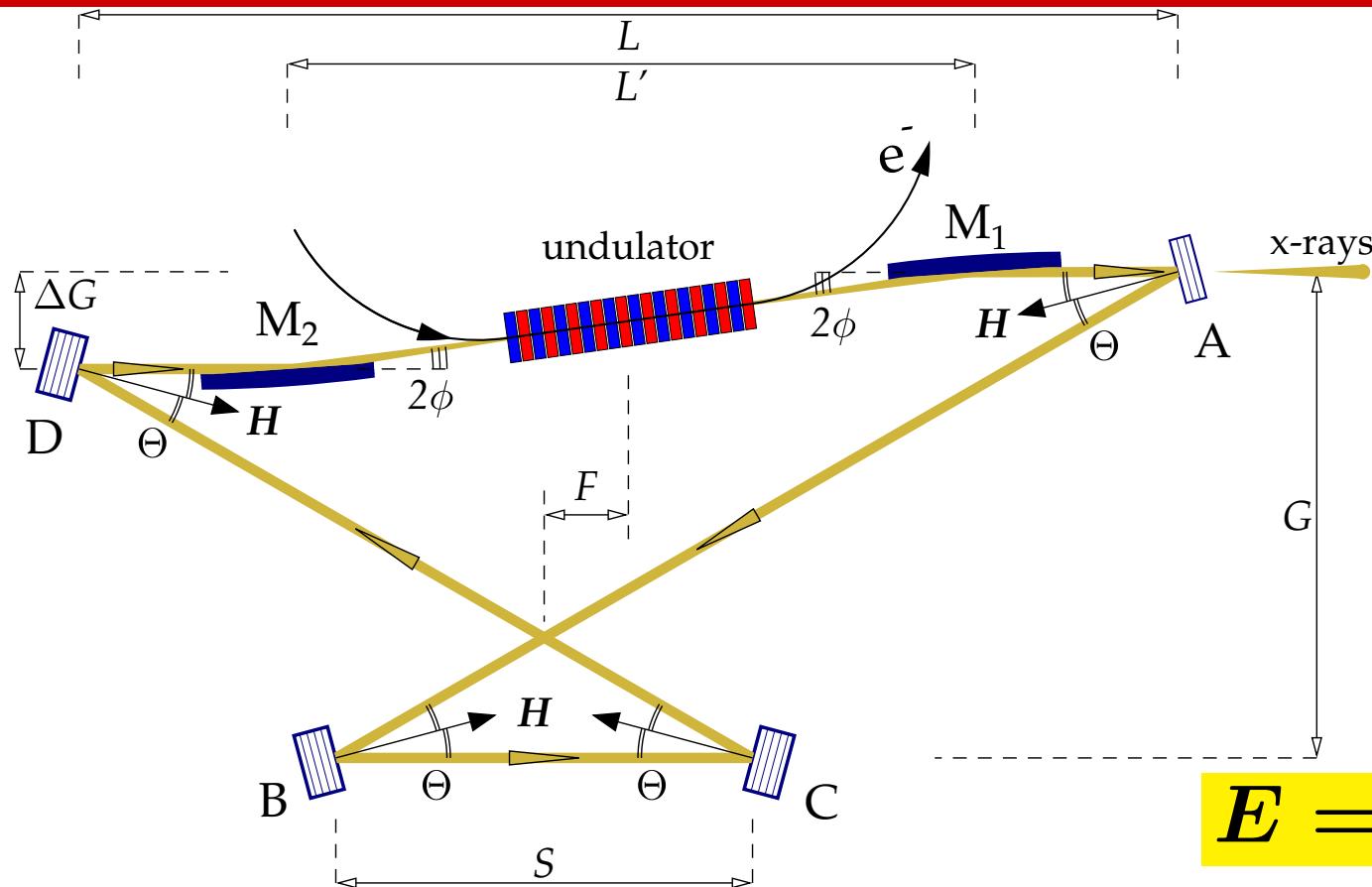


$$E = E_H \cos \Theta \Rightarrow \text{Two-crystal scheme is not tunable.}$$

Because, it is necessary to keep small $\phi \lesssim 2$ mrad

and therefore small $\Theta \lesssim 2$ mrad, for high reflectivity of the mirrors.

Tunable Cavity



A four-crystal (**A,B,C, and D**) x-ray optical cavity allows photon energy **E** tuning in a broad range by changing the incidence angle **Θ**.

R.M.J. Cotterill, Appl. Phys. Lett., 12 (1968) 403

K.-J. Kim, and Yu. Shvyd'ko, Phys. Rev. STAB (2009)

XFELO Simulations

R. Linberg, K.-J. Kim, W. Falley, Yu. Shvyd'ko

■ Undulator:

$$\lambda_u = 1.76 \text{ cm} \quad K = 1.5$$

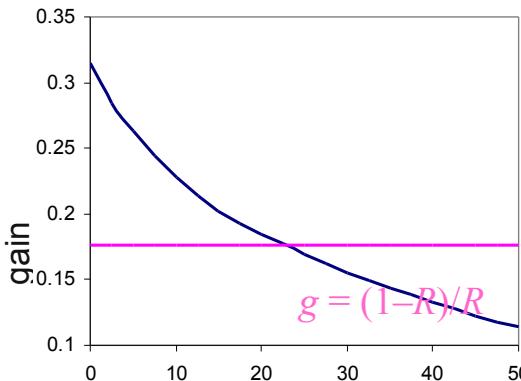
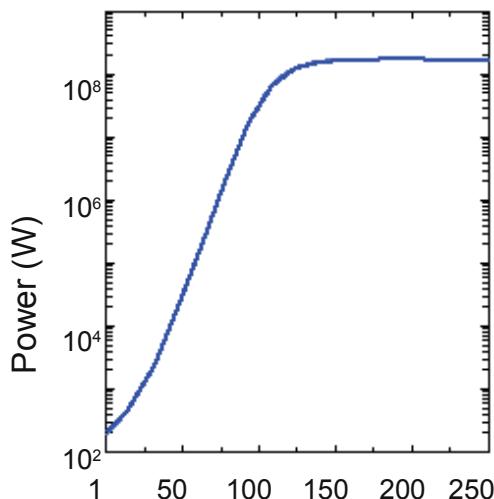
■ Electron beam:

$$I = 10\text{A} \quad \epsilon_x = 2 \times 10^{-7} \quad \beta_x = 10 \text{ m}$$

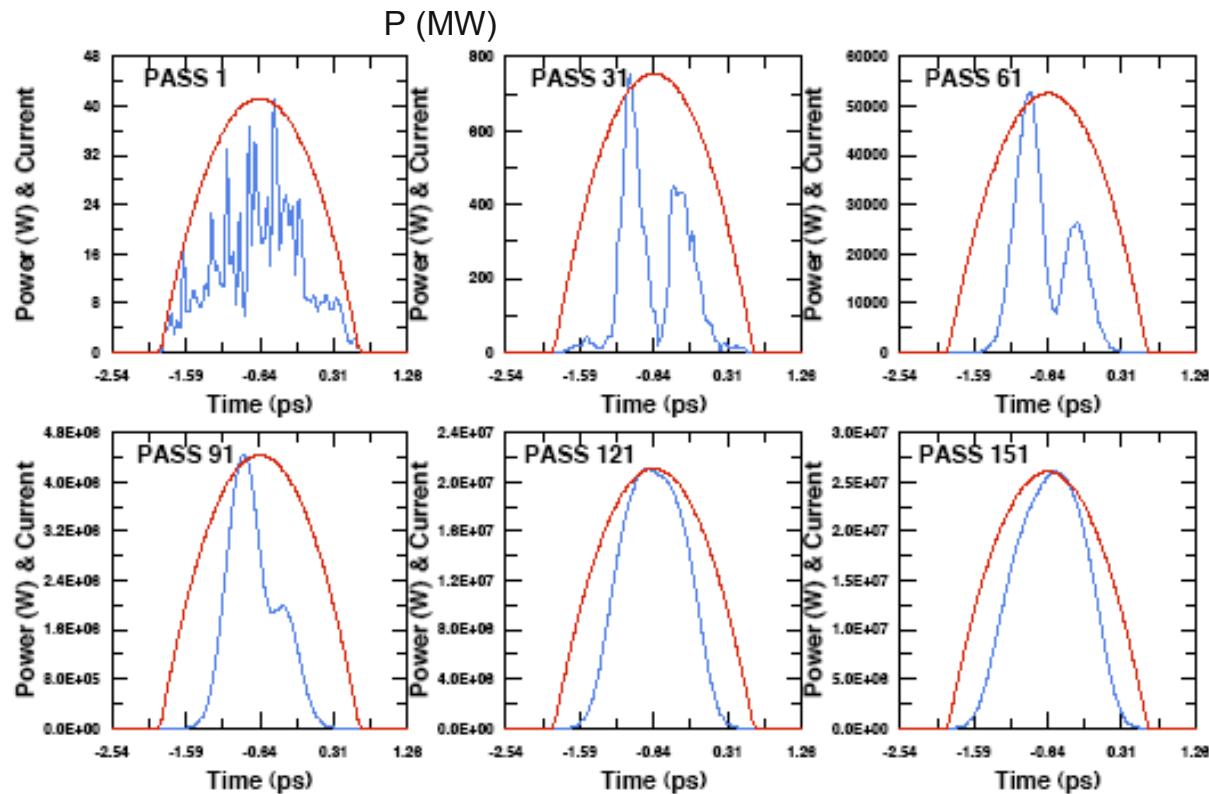
■ Bragg crystal:

Diamond, $\tau_M \approx 100 \text{ fs}$

GINGER simulation shows evolution from noise to power levels near those expected

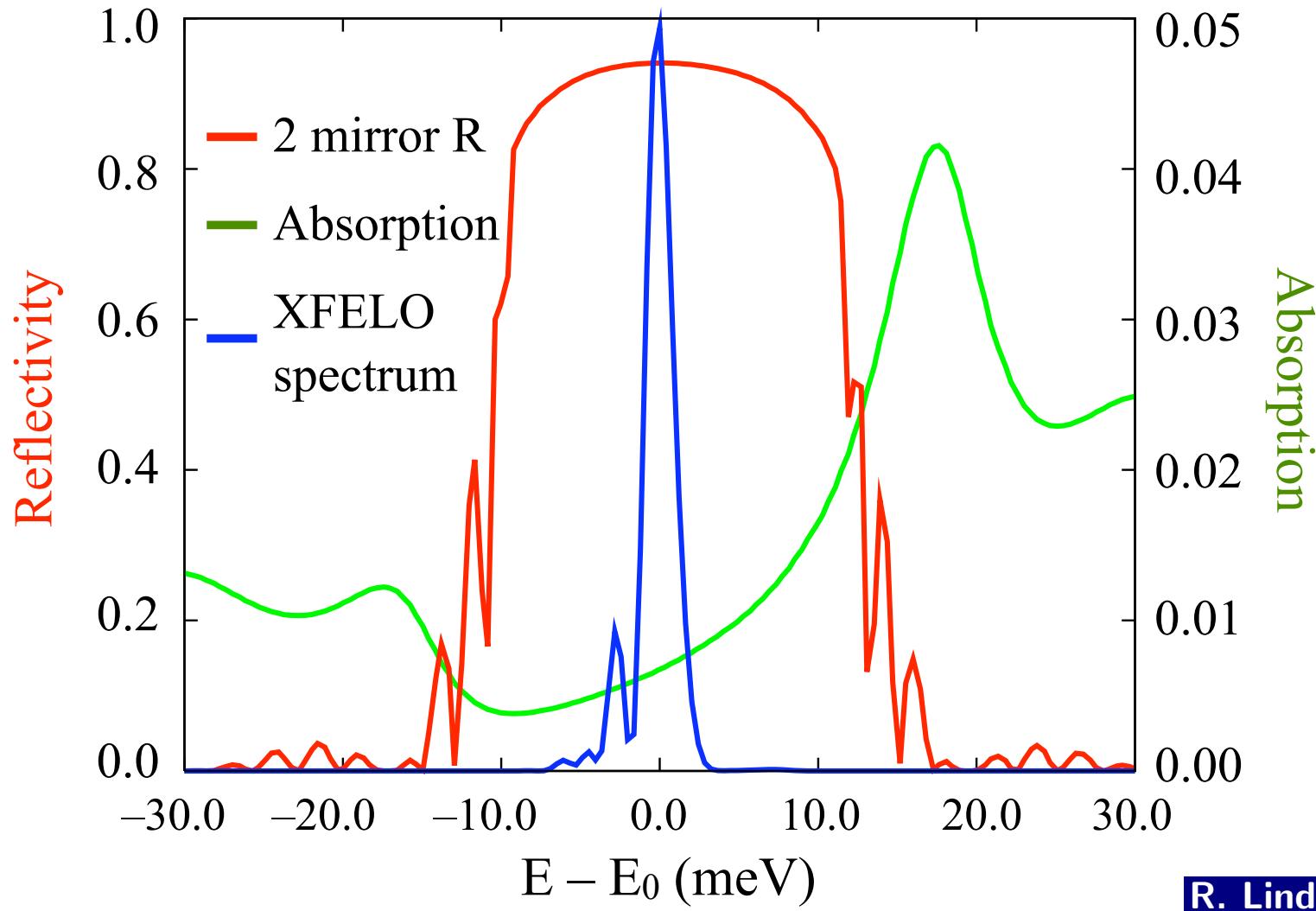


Single slice gain calculations indicate saturation power ~23 MW for mirror losses = 85%



XFELO Spectrum

After 500 passes in 2-crystal diamond cavity:



XFEL-O Performance

- Photon spectral range: $2 \lesssim E \lesssim 25$ keV.
- Full transverse and temporal coherence of ≈ 1 ps (rms) $\Rightarrow \Delta E \simeq 2$ meV.
- 5×10^8 photons/pulse (1 μ J/pulse)
- Peak spectral brightness comparable to SASE XFEL.
- Repetition rate $\gtrsim 1.5$ MHz $\Rightarrow (7.5 \times 10^{14} \text{ ph/s} = 1.7 \text{ W})$ average spectral brightness factor $\simeq 10^5$ larger than SASE XFEL, and comparable to the seeded SASE XFEL.
- Being operated at 14.4 keV, XFEL-O would generate $\approx 10^3$ Mössbauer photons per pulse with a 5 neV spectral width, the natural width of the 14.4 keV nuclear resonance in ^{57}Fe . With a repetition rate of $\gtrsim 10^6$ Hz, the XFEL-O would produce about 10^9 fully coherent 14.4 keV Mossbauer photons per second.
- Tunable.

Science drivers for XFEL-O

Many x-ray spectroscopies and techniques require hard x-rays ($E \gtrsim 2$ keV) with very narrow energy bandwidth $\Delta E \lesssim 1$ meV i.e. temporal coherence $\gtrsim 1$ ps:

- Inelastic x-ray scattering (IXS).
- Nuclear resonant scattering (NRS).
- HAXPES (hard-xrays photoemission spectroscopy).
- Imaging with hard x-rays at near-atomic resolution ($\simeq 1$ nm).
- Time-resolved (ps) measurements (structure, dynamics).
- Metrology: Mössbauer wavelength standard for atomic scales.
- etc, etc.

Technical Challenges

Ultra-low emittance injector.

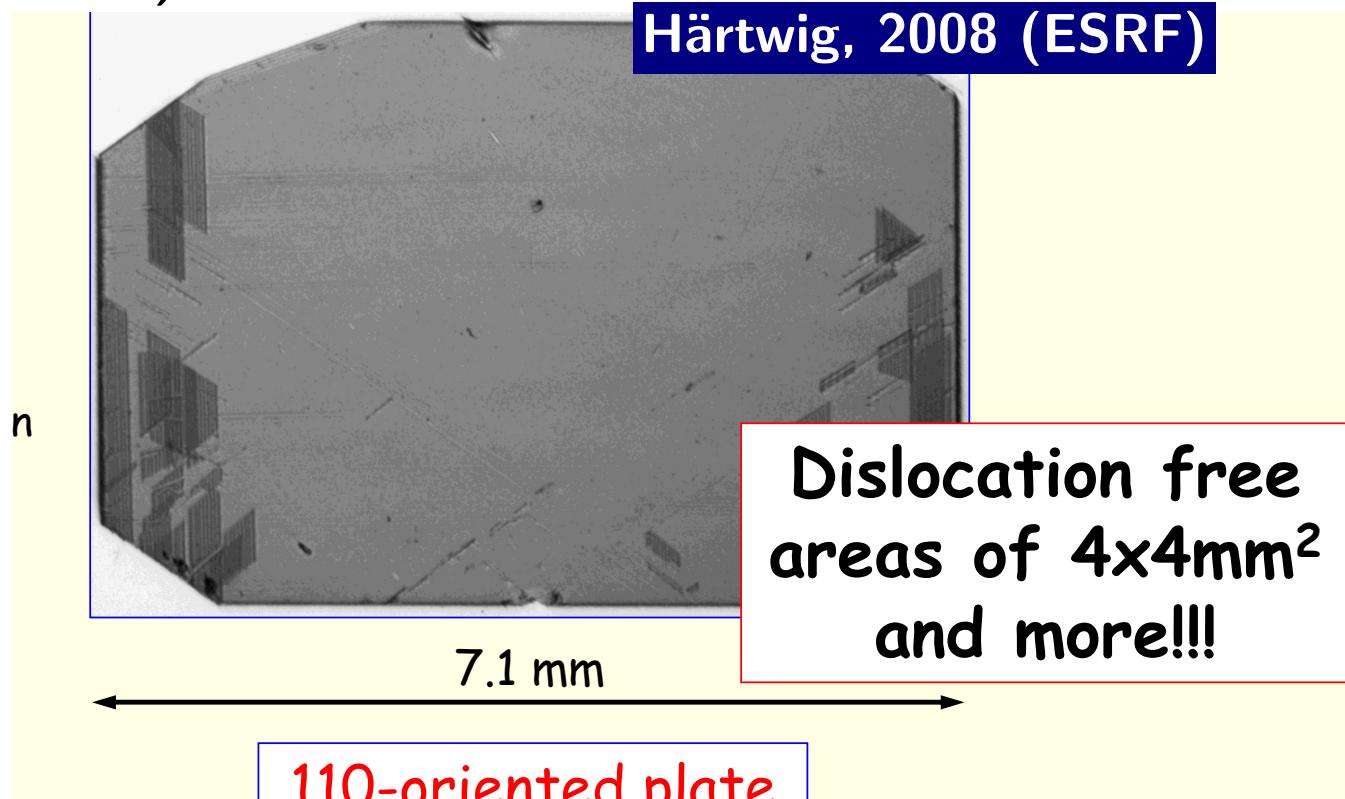
X-ray Optics:

- **Quality of diamond crystals:**
is the theoretical 99-98% reflectivity achievable?
- **Heat load problem (energy variations < 1 meV).**
- **Heat shock waves (energy variations < 1 meV).**
- **Angular stability: $\delta\theta < 10 \text{ nrad}$**
- **Spatial stability: $\delta L < 30 \mu\text{m} (\text{rms}) \rightarrow \delta L/L < 3 \times 10^{-7}$**

Quality of Diamond crystals

Required diamond crystals:

- high quality (dislocation free, etc.)
- thin: $10 - 40 \mu\text{m}$
- small suffice: $1 - 2 \text{ mm}^2$



Still open question:
is the theoretical 99-98% reflectivity achievable?

White beam topograph in transmission

Heat Load Problem

Temperature gradient $\delta T \Rightarrow$ energy spread $\delta E/E = \beta\delta T$.

Requirement: $\delta E < 1 \text{ meV}$, when the next pulse arrives.

Incident power $\simeq 50 \mu\text{J}/\text{pulse}$.

Absorbed power: $\simeq 1 \mu\text{J}/\text{pulse}$ (2%).

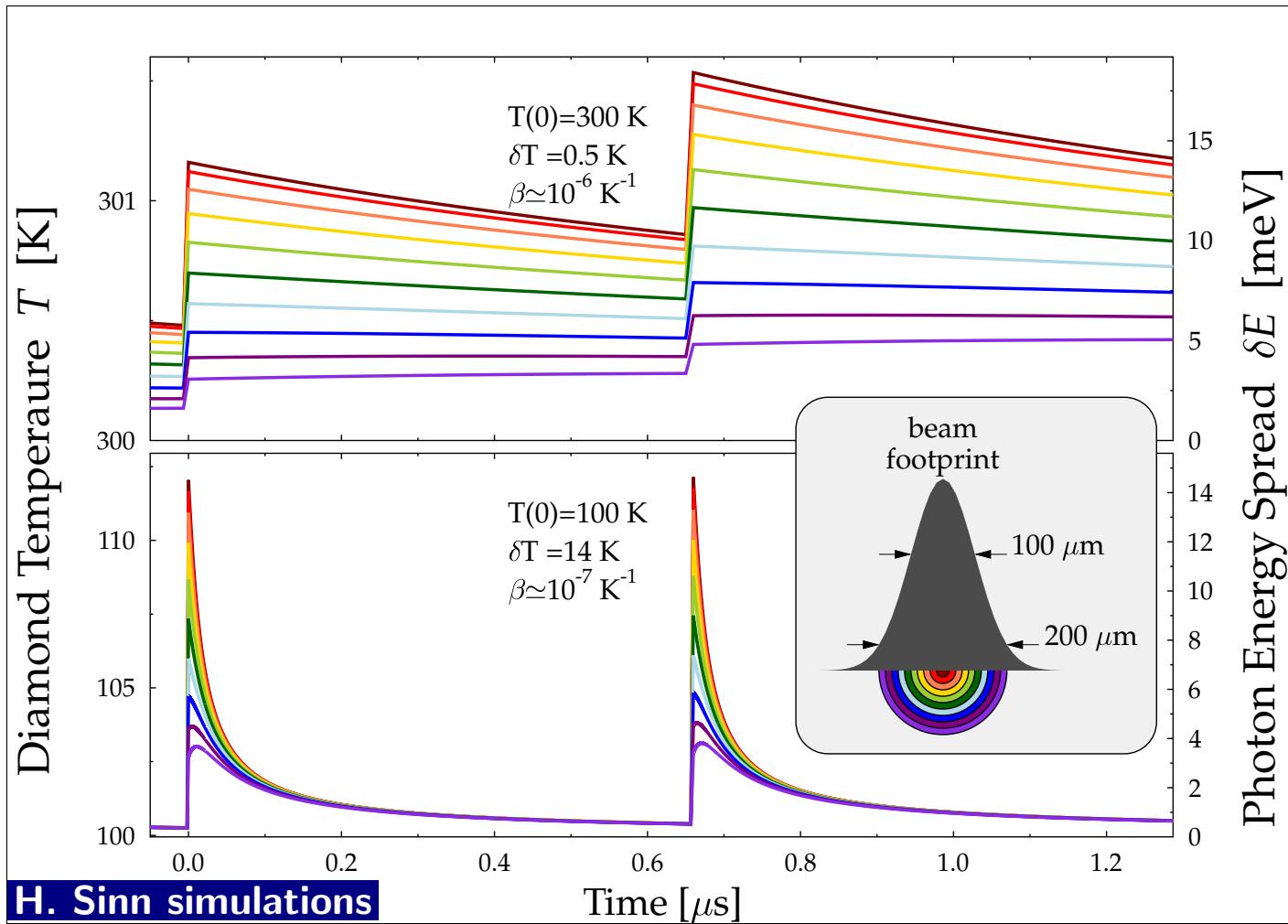
Footprint: $\simeq 100 \times 100 \mu\text{m}^2$

Is it a problem?

Heat Load Problem

Temperature gradient $\delta T \Rightarrow$ energy spread $\delta E/E = \beta\delta T$.

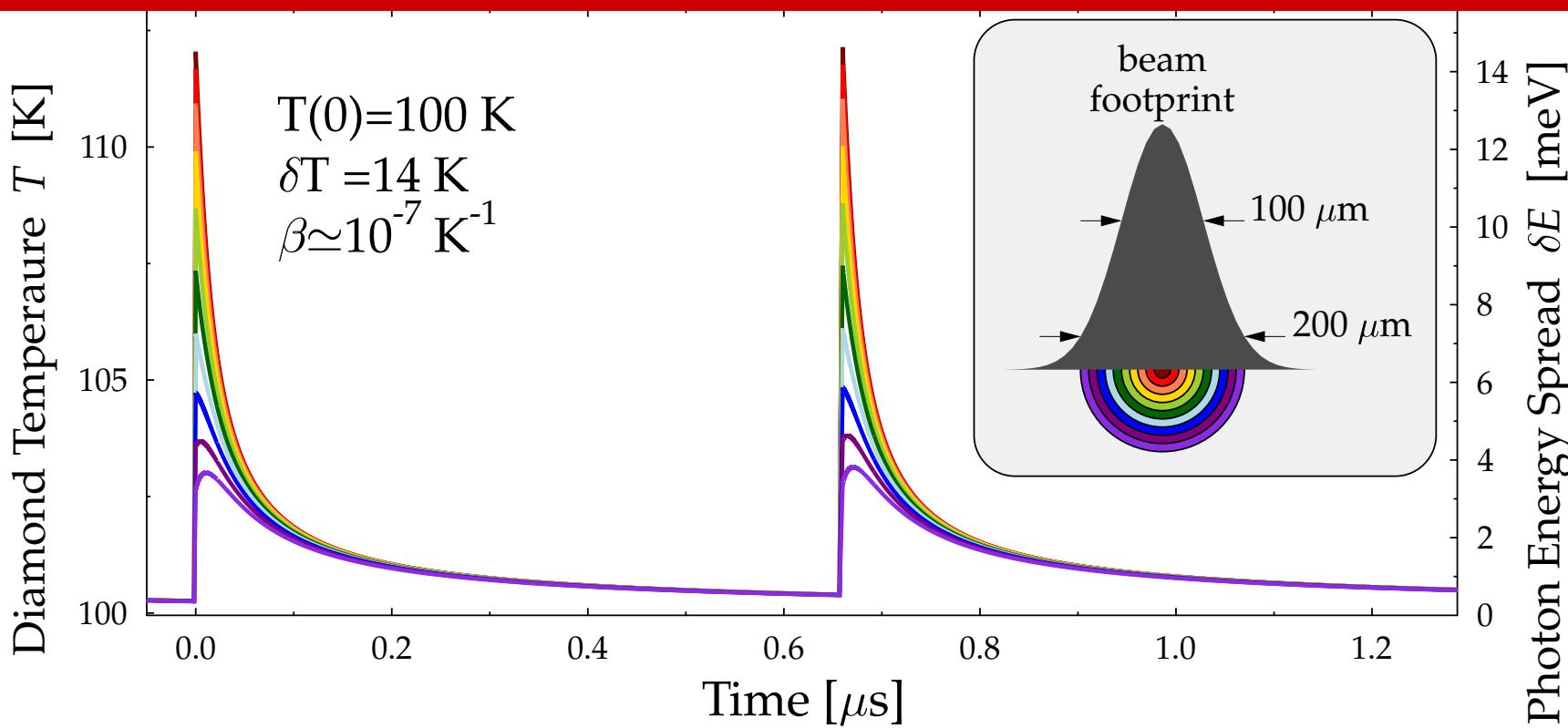
Requirement: $\delta E < 1$ meV, when the next pulse arrives.



- Big temperature jump δT after the x-ray pulse arrival.
- $T=300\text{K}$: Big temperature spread by the arrival of the next x-ray pulse.
- $T=100\text{K}$: Negligible temperature spread by the arrival of the next x-ray pulse.
- Reasons:
 1. High temperature diffusivity \mathcal{D}
 2. Low temperature expansion β

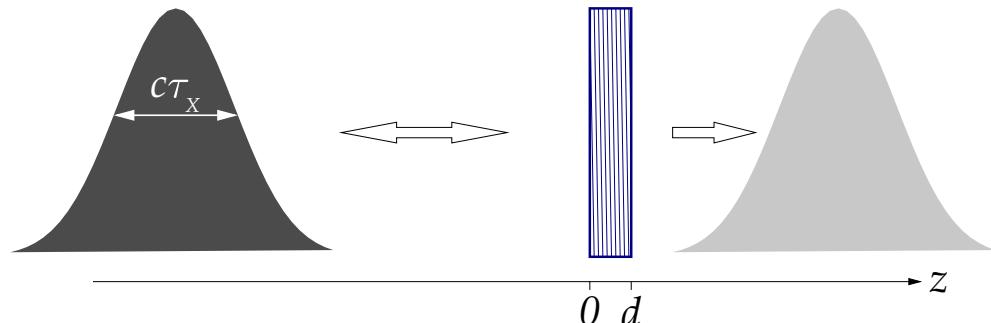
Solution: Maintain diamond at $T < 100$ K!

Heat Shock Waves



How fast the temperature jump δT results in thermal expansion and

in energy variation δE ?

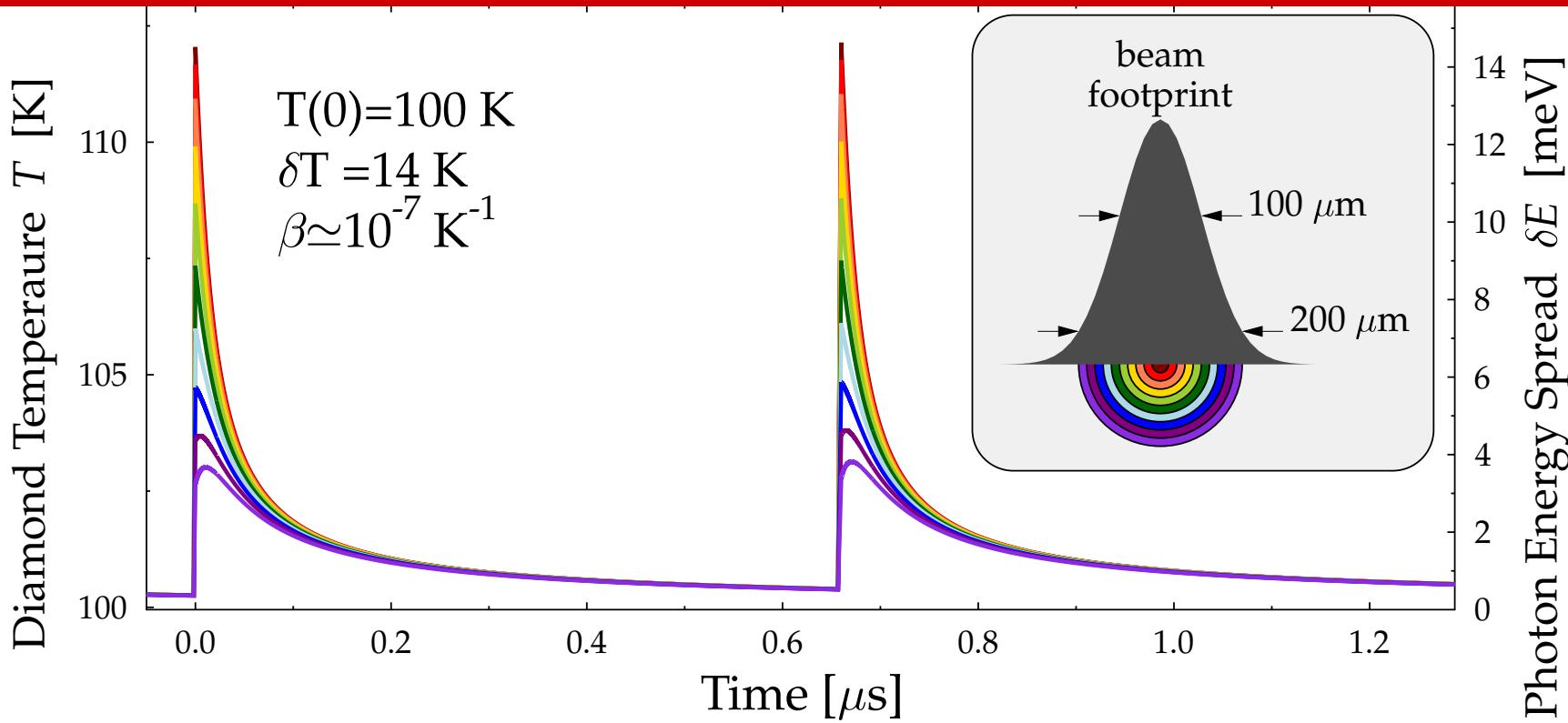


$$\tau_x = 1 \text{ ps (rms)} \Rightarrow c\tau_x = 300 \mu\text{m}$$

$$d \simeq 50 \mu\text{m}$$

Interaction time: $\tau_x = 1 \text{ ps (rms)}$

Heat Shock Waves



How fast the temperature jump δT results in thermal expansion and
in energy variation δE ?

Pedestrian: $\tau_D = \frac{d}{c_\ell} \simeq 2$ ns [sound velocity $c_\ell = 1.8 \times 10^4$ km/s]

Y.C.Lee: $\tau_D^* = \tau_D \frac{1}{\beta \Delta T} \simeq 1$ ms [J. Phys.: Cond. Matter: 20 (2008) 055202]

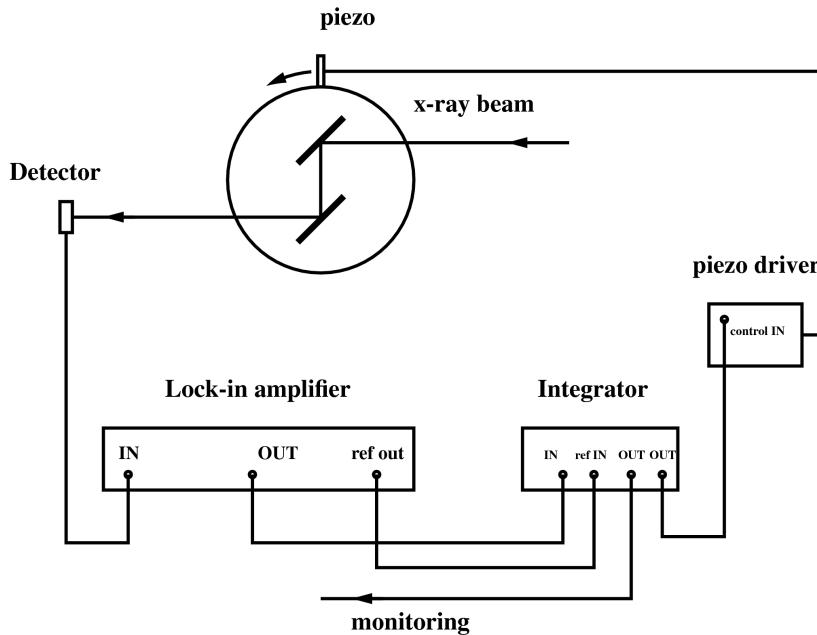
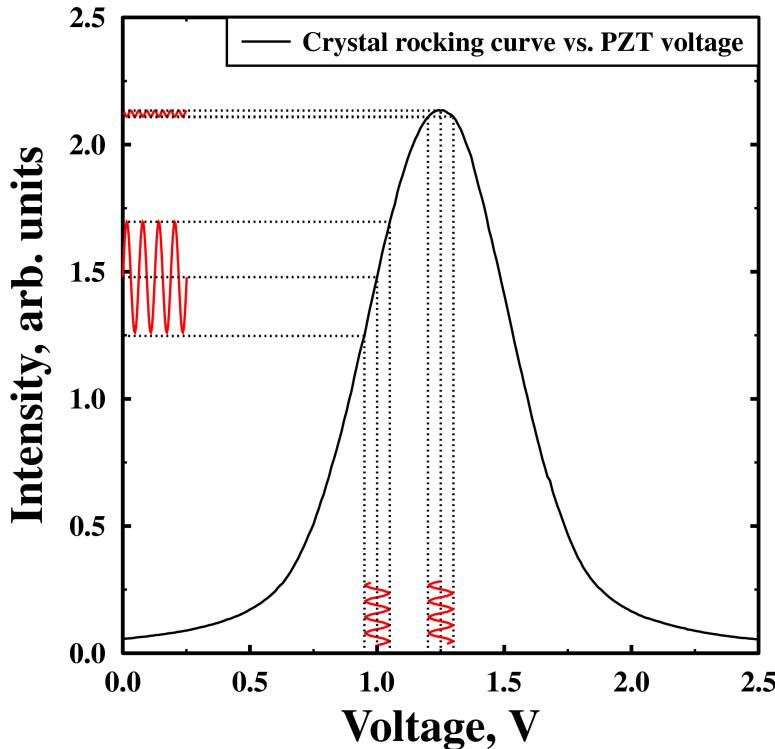
Thermal expansion is yet negligible while the pulse is on $\tau_x \ll \tau_D \ll \tau_D^*$!!!!

Angular & Spatial Stability

Required angular stability: $\delta\theta < 10 \text{ nrad}$

Required spatial stability: $\delta L < 30 \mu\text{m} (\text{rms}) \Rightarrow \delta L/L \simeq 3 \times 10^{-7}$ ($L = 100 \text{ m}$)

Solution: Null-detection hardware feedback. (LIGO prototype)



70 nrad stability is demonstrated at Sector 30

S. Stoupin, F. Lenkszus, et al.

- Transmitted x-ray intensity: the linear response to a small oscillating signal is proportional to angular deviation from the maximum of the rocking curve
- Feedback/correction signal is extracted using lock-in amplification

Summary & Outlook

XFEL-O:

- High spectral brightness.
- Small energy bandwidth.
- Full coherence. • ps-pulses.

Applications:

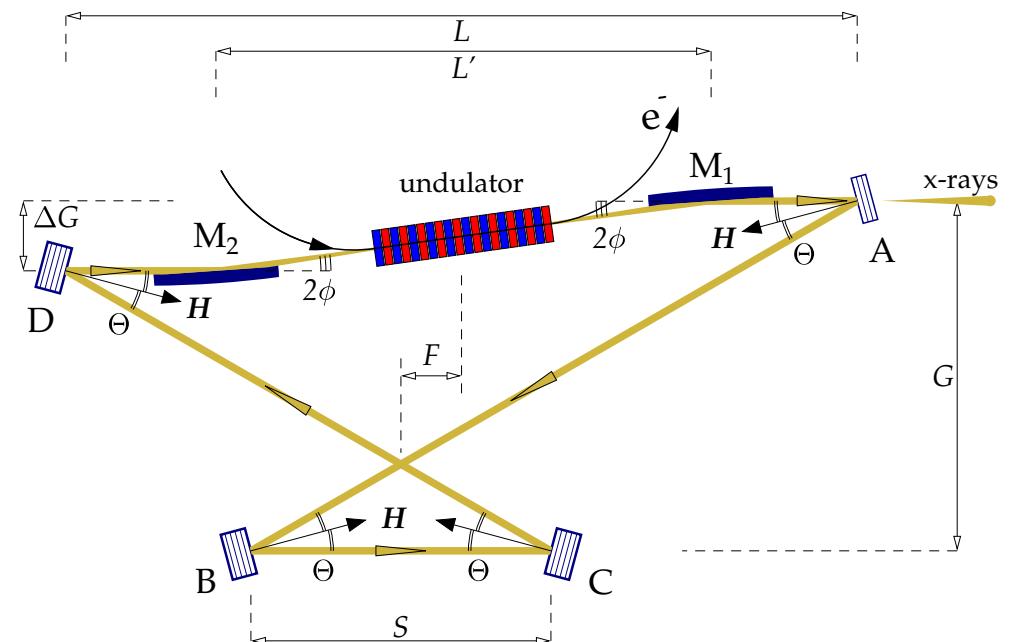
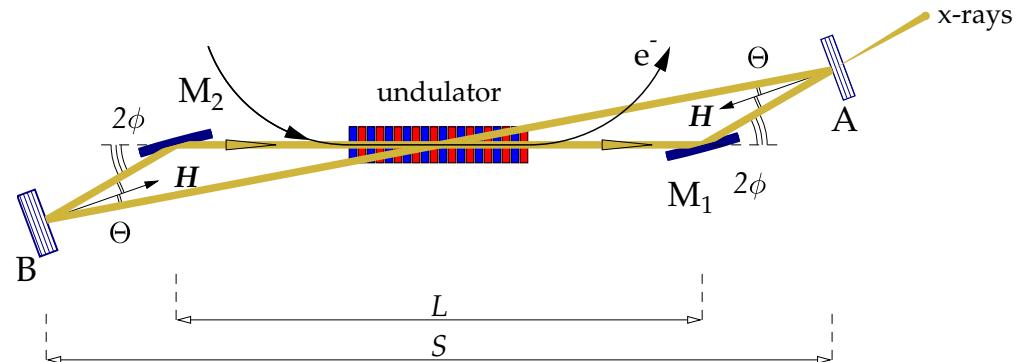
- Nuclear resonant spectroscopies.
- Inelastic X-ray scattering.
- HAXPES. • ps-Time measurements.
- Imaging at near-atomic resolution ($\simeq 1 \text{ nm}$).

Low loss x-ray cavities are feasible! X-ray cavities of different types for the XFEL-O under consideration, including tunable ones.

Challenges:

- Ultra-low emittance injector.
- Stability: thermal, angular, spatial, etc.
- Crystal quality.

XFEL-O R+D project is in progress at the APS.



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Lahsen Assoufid (APS)

Deming Shu (APS)